OLOGY DEPARTMENT

The

Geophysical Journal

of the

Royal Astronomical Society

incorporating

the Geophysical Supplement to the Monthly Notices of the R. A. S.

PUBLIC LIBRARY
FEB 6 1959
DETROIT

Volume 1 No. 4 December 1958

Published and Sold by the

Royal Astronomical Society

Burlington House, London, W.1, England

Price £1; in U.S.A. $3 Annual Subscription £3; in U.S.A. $9

OCCASIONAL NOTES

of the

ROYAL ASTRONOMICAL SOCIETY

The following issue of *Occasional Notes*, which is a publication consisting of authoritative but non-technical reviews of astronomical and geophysical topics, is now available.

Vol. 3. No. 20. November 1958

Contents

A. D. THACKERAY, Radial Velocities
D. W. COLLINSON, Rock Magnetism
OLIN J. EGGEN, Flamsteed and Halley

Price 5*s.* 0*d.* (in U.S.A. $0·90)

All earlier issues of *Occasional Notes* are in print, and complete sets (Nos. 1–19) are available, price £3 7*s.* 6*d.* (in U.S.A. $10).

Orders should be addressed to:

THE ASSISTANT SECRETARY
Royal Astronomical Society, Burlington House, London, W.1.

Geophysical Journal

Papers offered for publication in the June 1959 issue should reach the Assistant Secretary of the Society by mid-February

The Geophysical Journal

of the

ROYAL ASTRONOMICAL SOCIETY

Vol. 1 No. 4 December 1958

Tidal Mixing in the Narrows of the Mersey Estuary

P. Hughes

(Received 1958 June 2)

Summary

Observations of salinity in the Narrows of the River Mersey have shown that vertical mixing due to tidally induced turbulence may be complete at mid-tide. As tidal currents abate horizontal differential velocities, which constitute a seaward flow in the upper layer and an upriver flow near the bottom, become apparent and produce vertical salinity gradients. A second series of observations showed that vertical homogeneity may not be reached at any stage of the tide if the riverflow is high. Applying the theory for a vertically mixed estuary, coefficients of longitudinal eddy diffusion were computed for a low riverflow of 26 m^3/s and gave a mean value of 160 m^2/s. During a period of greater fresh water influx (103 m^3/s) when conditions were less clearly defined, the average coefficient was considerably higher at 360 m^2/s.

1. Introduction

The part of the Estuary of the River Mersey called the Narrows is a straight deep channel, with a fairly regular bottom, which connects Liverpool Bay with the upper basin. From New Brighton the Narrows extends 9·7 km (6 ml) upstream and is only 1·2 km wide at its narrowest, although in places at low water the depth exceeds 21·3 m (70 ft). The estuary then widens into the upper basin extending as far as Howley weir, Warrington, above which the river is non-tidal except for very high tides. The upper basin has a maximum width of about 4·8 km (3 ml) but it is shallow, and at low water many sandbanks can be seen and the water in the channels is usually only a few metres deep.

For a tide reaching 9·4 m (31 ft) above the Liverpool Bay Datum at Princes Stage, Liverpool, the intertidal capacity of the estuary above Rock Light, New Brighton, is about 550×10^6 m^3 whereas at low water the capacity is only about 150×10^6 m^3. The high-water capacity from the Rock Light, New Brighton, to a

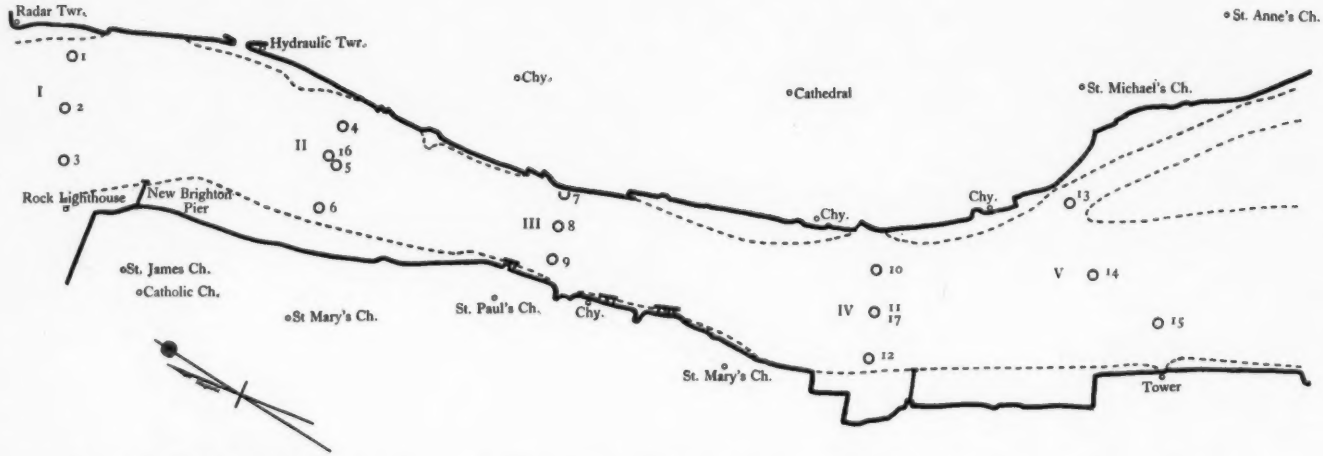


FIG. 1.—Sampling stations in the narrows of the Mersey. Dotted lines indicate approx. L.W. level of a 30 ft tide at Liverpool. (Scale 1 in to 1 statute mile)

section 8 km upriver is $195{\cdot}4 \times 10^6$ m^3, whereas the low-water capacity is 99×10^6 m^3. Therefore the mean volume of water in this region is $147{\cdot}2 \times 10^6$ m^3 and the intertidal volume is 96.4×10^6 m^3. From these data the mean current over a 9·4 m flood or ebb tide may be computed. Considering first the largest cross-section at Rock Light, which has a mean area of $24{\cdot}7 \times 10^3$ m^2, the mean current is 1·0 m/s, and assuming a sinusoidal variation of tidal current the maximum current is 1·6 m/s. Similarly for the smallest cross-section, which is situated 4 km from Rock Light and has a mean area of 15×10^3 m^2, the mean current is estimated at 1·4 m/s and the maximum current at 2·2 m/s.

The riverflow due to the influx of fresh water from the run-off areas is small compared with the large tidal currents. For the first series of observations in 1956 May the flow amounted to 25·7 m^3/s whereas between 1957 March 17 and 23 it varied from 205 to 68 m^3/s.

The observational programme described here was by way of a reconnaissance, with a view to a more detailed study of mixing processes. The Narrows was chosen as the shape of the channel is simple, whereas the rest of the estuary presents a complicated system of varying width and depth. Moreover, being a small area it was possible to obtain a detailed picture of the variables concerned in a short time.

2. Observations of temperature and salinity

Sampling of the estuarine water was carried out from a survey launch provided by the Mersey Docks and Harbour Board, between 1956 May 22 and 1956 May 28, and again on 1957 March 21 and 22. The approximate positions of sampling are shown in Figure 1. At each station samples were obtained from the surface, mid-depth and 1·2 m (4 ft) above the bottom. The surface sample was taken with a canvas bucket, while the other two were collected with a Nansen–Pettersson insulating water bottle. In the first series, one cross-section of the river was covered each day by sampling at three stations, one fairly close to each bank and the other in the middle. A station was occupied every half hour, so that surface, intermediate and bottom samples were obtained every hour in the middle and every two hours at each of the outer stations. The operation was repeated on different days. For sections I and II, ebb tides only were observed, at III a whole tidal cycle was sampled, while at IV and V observations were carried out over flood tides. The period was chosen because the predicted variation of tidal range was small. The changes from one tidal cycle to the next were observed by a series of surface samples taken at New Brighton pier.

The results indicated that for the second series, taken during a period of fairly high fresh-water influx in 1957 March, it was sufficient to sample at a mid-river station at each end of the Narrows.

Temperatures were measured with mercury-in-glass thermometers and are correct to 0·1 °C. The salinity of each sample was measured in the laboratory by an electrical conductivity method. The apparatus consisted of a high quality resistance bridge with a 600 c/s tone source and an earphone detector. The sample was contained in a glass cell and the resistance between two platinum electrodes in this cell constituted the unknown arm of the bridge. Calibration was effected by using diluted sea-water of known salinity. The electrical conductivity is sensitive to temperature changes and it was necessary to maintain the temperature of the cell to within 0·01 °C in order to give an accuracy of 0·05 per cent in the salinity.

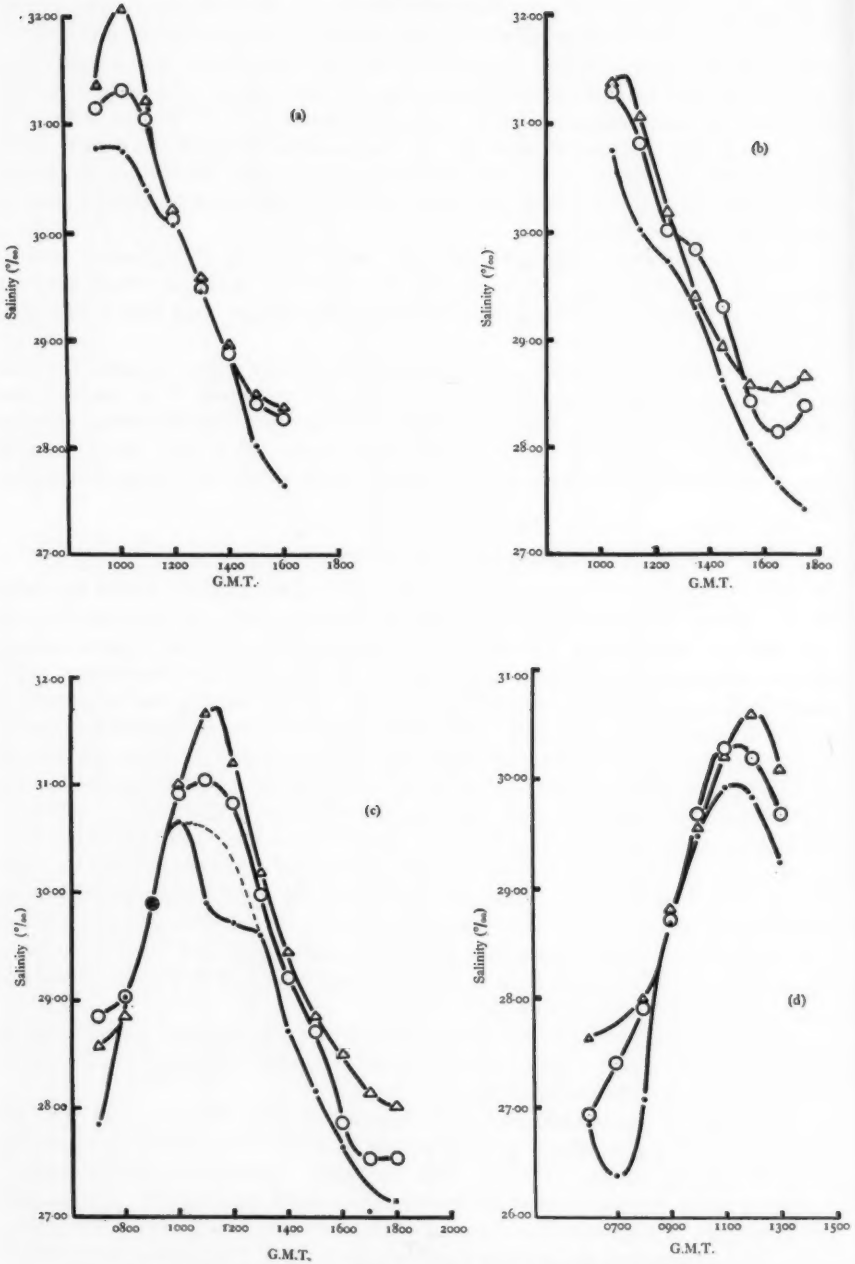


FIG. 2.—Variation of salinity with time at mid-river stations

(a) Station 2, 1956 May 22, (b) Station 5, 1956 May 23,
(c) Station 8, 1956 May 24, (d) Station 11, 1956 May 25.

— ● — surface, — ○ — intermediate, — Δ — bottom.

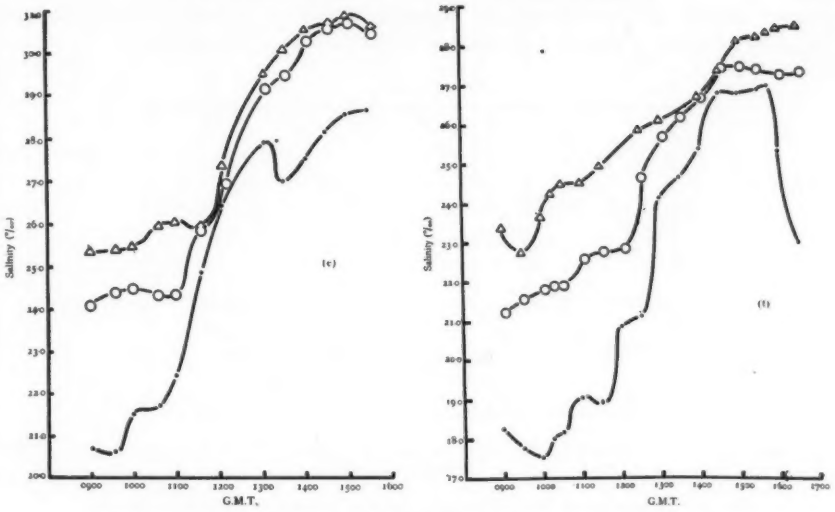


Fig. 2. *Contd.*—Variation of salinity with time at mid-river stations
(e) Station 16, 1957 March 21, (f) Station 17, 1957 March 22.
— ● — surface, — O — intermediate, — Δ — bottom.

3. The distribution of salinity, temperature and density

The salinity distribution during the period of the first series of observations in 1956 May will be considered first. The variation of salinity with time and depth at each mid-river station is shown in Figure 2(a) to (d). The increase in salinity at all levels as the tide floods and its decrease as the tide ebbs is obvious. The difference between the extreme values over a tidal cycle is about 4 parts per thousand (‰). The kink in the curve of surface salinity at Station 8 on May 24 was probably due to the local influx of fresh water across the surface during a rain shower. The variation of salinity with depth was small or absent when the tidal current was strong, so that for the mid-tide period the isohalines were sensibly vertical. Near high and low water, however, there were significant salinity gradients, with the salinity increasing from the surface to the bottom.

Because of the small number of observations, only a qualitative study of the difference of surface salinity across the Narrows was possible. It shows on the average a small increase from the Liverpool to the Birkenhead side of the river. The concentration of fresher, lighter water on the right-hand side of a wide estuary, looking in the direction of the residual flow, has been observed previously and is probably due to the Earth's rotation (Pritchard 1955). In the narrow channel under consideration, however, this phenomenon may be due to local topographical effects and there are too few observations on which to base a definite conclusion.

An attempt has been made to present a synoptic picture of the salinity distribution in a vertical section along the middle of the Narrows at the time of high and low water (registered on the Princes Stage tide gauge). Corrections were applied for the change in conditions over the period of observations by referring to the

surface salinity at New Brighton. Despite a few irregularities, the isohaline diagrams (Figures 3 and 4) give a clear indication of stratification.

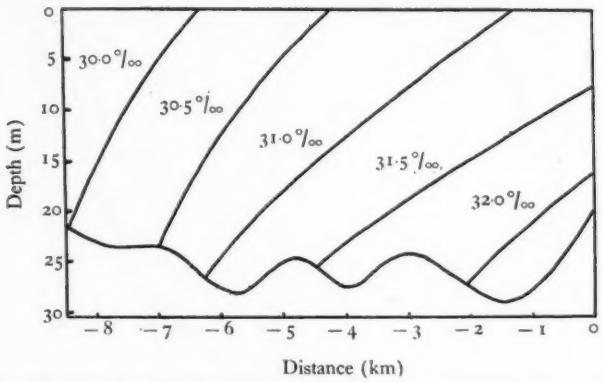


FIG. 3.—Isohalines at high water in a vertical section along the middle of the Narrows (distance in km from Rock Light, New Brighton).

The salinity differences between surface and bottom were not at a maximum at high or low water, but continued to increase to about 1 °/₀₀ some 40 min after high water, and to more than 1 °/₀₀ over one hour after low water. The time differences given here are averages of the available observations, and typical variations of salinity with time between surface and bottom are given in Figure 5.

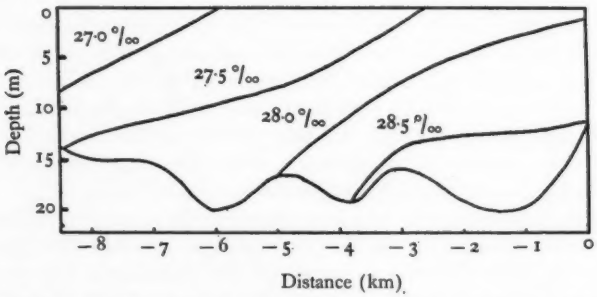


FIG. 4.—Isohalines at low water in a vertical section along the middle of the Narrows (distance in km from Rock Light, New Brighton).

From the salinity data for each cross-section, a mean value over a tidal cycle was obtained. Where observations extended over part of a tidal cycle extrapolation was necessary. The observations at New Brighton were used again to correct for the variation in the tides and meteorological conditions during the sampling period. The final mean salinities $\bar{S}$ are shown in Figure 6, as a function of distance along the Narrows. The main point of interest is that, excluding the innermost

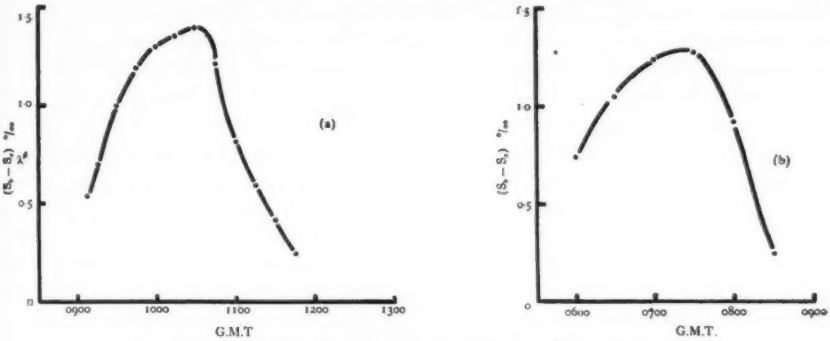


FIG. 5.—Surface (S_0) and bottom salinity (S_b) differences.
($S_b > S_0$ then difference > 0).
(a) 1956 May 22, H.W. 0922, (b) 1956 May 25, L.W. 0553.

section, the salinity gradient along the limited portion of the estuary was sensibly constant. The salinity distribution is given by

$$\bar{S} = 30{\cdot}11 + 0{\cdot}236x$$

where x is measured in kilometres from Rock Light, New Brighton, positive to

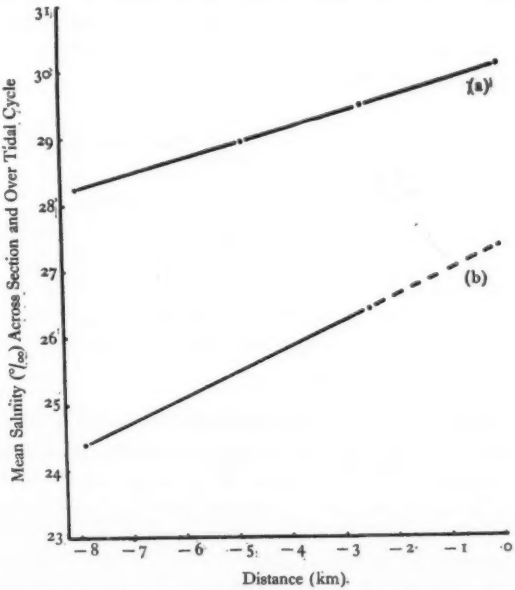


FIG. 6. Distribution of mean salinity along the Narrows (distance in km from Rock Light, New Brighton).
(a) 1956 May, (b) 1957 March.

seaward. The mean fractional fresh-water concentration, $\bar{f}$, over a section, may be determined from the following relation:

$$\bar{f} = \frac{S_0 - \bar{S}}{S_0}.$$

The source sea-water, S_0, was taken as the mean surface salinity during the period of observations at the Liverpool Bar Light Vessel, which is stationed about 22·5 km (14 naut. ml) outside the estuary. S_0 was found to be 31·68 $^{\circ}/_{\circ\circ}$ and thus

$$\bar{f} = 0{\cdot}049 - 0{\cdot}007449x.$$

The observations made on 1957 March 21 and 22, when the riverflow was substantially higher, will now be considered. Only two sampling stations were used and a linear distribution of salinity along the Narrows was assumed. As before, corrections for non-stationary conditions were applied to the mean salinity. The results are shown in Figure 2 (e) and (f), and indicate a steeper mean horizontal salinity gradient and lower overall values of the mean salinity. At each of the two mid-river stations a vertical salinity gradient was always apparent and there was thus no period when the isohalines were vertical. The differences in salinity between surface and bottom at slack water were larger than obtained in the previous series of observations. The salinity distribution is given by

$$\bar{S} = 27{\cdot}36 + 0{\cdot}375x.$$

The variations of temperature were comparatively small, but where a salinity gradient existed a decrease in the temperature from the surface to the bottom was generally observed. At any station the temperature decreased on the flood tide and increased again on the ebb tide, with a total range of little more than 1° C. The vertical temperature gradient at high water was of the order of 0·02° C/m.

Following the normal oceanographic practice the density is expressed in the contracted form, σ_t, defined by the equation

$$\rho_{s,} = \left(1 + \frac{\sigma_t}{1\,000}\right) \text{ g/cm}^3$$

where $\rho_{s,t}$ is the density at atmospheric pressure for a salinity S $^{\circ}/_{\circ\circ}$ and a temperature t °C. This dependence of σ_t on the salinity and the temperature has been determined experimentally and is tabulated (Knudsen 1901; Mathews 1932).

The distribution of σ_t in a vertical section along the middle of the Narrows at high and low water, which has been computed from the temperature and salinity data, is shown in Figures 7 and 8. There is a close resemblance between the distributions of the salinity and the density.

4. Computation of the apparent longitudinal eddy diffusivity

Stommel's theory of mixing in a vertically homogeneous tidal estuary has the advantage that no assumption is made about the physical nature of the longitudinal diffusivity, which is deduced from the observed distribution of fresh water (Stommel 1953). To a certain extent the diffusion of a pollutant in a tidal estuary may be similar to its diffusion in turbulent pipe flow, for which a theory has recently been given by Taylor (1954). He has shown that the apparent longitudinal component of turbulent diffusion depends on a balance between the transverse diffusion and the advection due to the variation of the mean velocity across a section. The theory has been extended by Ellison (1957) to the case of a broad open channel, but the mean velocity profile and the vertical eddy diffusivity must be known in order to obtain numerical values of the longitudinal diffusivity. Moreover in these treatments the advection is due to the variations in the velocity caused by the friction at the boundary, but where there is a density gradient a further source of

advection exists which may be more important. In the estuary under consideration little is known of these quantities, and it is impossible at the present time therefore to make more than a qualitative use of the ideas. The data have been analysed on the lines of Stommel's theory to give empirical values of the apparent longitudinal diffusivity, it being understood that these values may include the effects of the physical processes discussed.

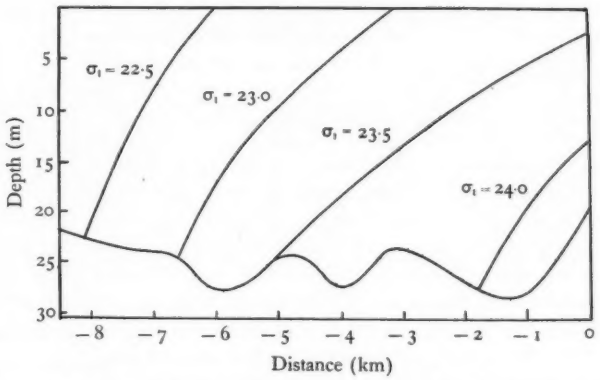


FIG. 7.—The distribution of the density, σ_t, at high water in a vertical section along the middle of the Narrows. (Distance in km from Rock Light, New Brighton).

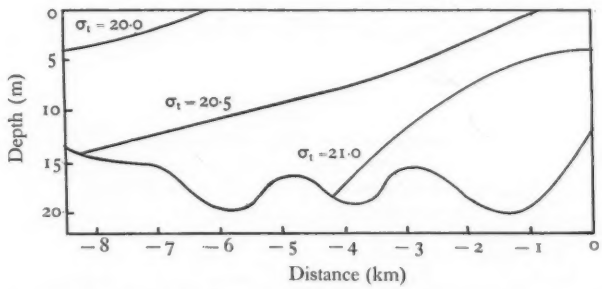


FIG. 8.—The distribution of the density, σ_t, at low water in a vertical section along the middle of the Narrows. (Distance in km from Rock Light, New Brighton.)

In Stommel's theory of tidal mixing it is assumed that (*a*) changes in salinity both vertically and horizontally across the estuary are small compared with those along the river and (*b*) conditions do not change from one tidal cycle to the next.

The net flux of a pollutant, $F(x)$ depends on the transport *downstream* by the river flow R, and the effective turbulent diffusion *upstream* due to tidal mixing. This is expressed in the equation

$$F(x) = Rc - KA\frac{dc}{dx},$$

where c is the concentration of pollutant, A is the cross-sectional area of the section

under consideration and K is the longitudinal coefficient of eddy diffusion. If the fresh-water content is considered as the pollutant then

$$F(x) = R = Rf - KA\frac{df}{dx}$$

and

$$K = -\frac{R(1-f)}{A(df/dx)},$$

from which K may be computed.

The estimation of riverflow followed the method described in the Water Pollution Research Technical Paper No. 7 (H.M.S.O. 1938), where the flow from each of the streams making a contribution to the total influx of fresh water into the Estuary was considered. When gaugings were not available, estimates of flow based on the size and character of the drainage area were used. During the first period of observations the riverflow was small with an average of 25·7 m³/s. On the other hand, in 1957 March the riverflow was changing fairly rapidly and dropped from 205 m³/s on March 17, to 68 m³/s on March 23. In view of the change in conditions K for this period was computed from two values of the riverflow R, namely 103·1 m³/s, which is the average for the two days of observations, and 151·8 m³/s, the average over the period March 16 to March 22.

The mean cross-sectional area, over a tide, for any position was calculated from the cross-sectional areas at high water and low water on a tide reaching 31 ft at Princes Stage. This information was made available by the Marine Surveyor (Mersey Docks & Harbour Board).

The computed values of the eddy diffusivity are given in Table 1.

Table 1

Computation of eddy diffusivity

Date	Distance from New Brighton (km)	Cross-sectional area 10^3 m²	K_n (m²/s)	
			(R = 25·69 (m³/s))	
1956 May	0·0	24·7	132·8	
	−2·6	19·4	165·4	
	−4·85	17·0	185·5	
	−8·0	19·1	160·8	
Mean $\bar{K}$			**161·0**	
			(i) (R = 103·05 (m³/s))	(ii) (R = 151·78 (m³/s))
1957 March	−2·4	19·7	368·1	542·2
	−7·9	19·15	349·6	515·0
Mean $\bar{K}$			**358·9**	**528·6**

For similar conditions of low riverflow the computed values of the coefficient of eddy diffusion are of the same order as those obtained by Stommel in his analysis

of Bassindale's River Severn salinity data. Stommel's values for K varied widely, and an average between his sections 13 and 20, where the fresh-water content was roughly the same as in the Narrows for the May sampling period, was $63{\cdot}8\,m^2/s$.

5. An estimate of the differential flow between surface and bottom

There is a tendency for fresher water to move seawards in an upper layer with an upriver flow of more saline water near the bottom. An estimate of the lower limit of this differential velocity may be made with reference to the high-water isohaline diagram and the curves showing the variation of salinity at different depths during a tidal cycle. On 1956 May 25 the salinity gradient was absent until an hour and a half before high water. From then until high water the differential flow increased the salinity gradient, despite the effect of turbulent mixing, until at high water a distance of 2 km separated the extremes of the 30·00 $^{o}/_{oo}$ isohaline. This implies a mean differential current between surface and bottom during the period of 37 cm/s. The action of turbulence before high water would tend to reduce the salinity gradient, so that the above estimate represents a lower limit. It must be noticed, however, that over a complete tidal cycle the mean current difference will be less.

6. Flushing time

The average length of time required for river water to move through a portion of an estuary is known as the flushing time T, and is given by the formula:

$$T = Q'/R,$$

where Q' is the total amount of river water accummulated in the region considered, in our case the Narrows, and R is the riverflow.

Results for the Narrows are set out in Table 2.

Table 2

	Mean $\bar{f}$	Mean vol. of water in Narrows	Q' Mean vol. of accumulated fresh water	R	T
1956		m^3	m^3	m^3/d	(days)
May 22–25	0·0795	$147{\cdot}2 \times 10^6$	$11{\cdot}7 \times 10^6$	$2{\cdot}22 \times 10^6$	5·3
1957					
March 21–22	0·2281	$147{\cdot}2 \times 10^6$	$33{\cdot}58 \times 10^6$	$8{\cdot}91 \times 10^6$	3·8
				$13{\cdot}12 \times 10^6$	2·6

For a low river flow it is seen that the average length of time for river water to move through the region is 5·3 days, which agrees fairly well with a value of 6·2 days given in the Water Pollution Research Technical Paper No. 7 (1938) for similar conditions. As might be expected, a larger river flow reduces the flushing time.

7. Discussion

Tidal currents in the Narrows of the River Mersey are mainly responsible for the turbulent mixing which takes place, while the seaward transport due to

the riverflow is comparatively small. One would expect therefore that the coefficients of eddy diffusivity computed from data obtained in 1956 May would characterize the state of mixing for most riverflows. The results of later observations do not support this conclusion, however, as the computed coefficients for 1957 March 20 and 21 are somewhat higher. The answer is perhaps that conditions in the Narrows did not strictly satisfy the initial assumptions of Stommel's theory, insisting as it does on stationary conditions and vertical homogeneity. The riverflow was lessening during the later set of observations while the samples taken at New Brighton suggest that the salinity was still adjusted to the higher riverflow. As regards the vertical distribution of salinity, it can be seen that during the two day sampling period the water did not become vertically homogeneous, even at times of maximum horizontal tidal current. The effects of tidal mixing were still clear, however, as the large difference in salinity between surface and bottom, which occurred near low water, became smaller as the tidal currents increased. This decrease continued until about one and a half hours before high water in one case, and about two and a half hours in the other, when minimum differences were observed.

In an estuary which has a source of fresh water at one end and pure sea-water at the other, the absence of stratification indicates intense vertical turbulence. If there is very little turbulence the motion produces a two-layer system. Vertical mixing raises the potential energy of a column of stratified water and the energy is derived from the kinetic energy of the turbulence or from the mean motion (Proudman 1953). Differential movements between surface and bottom always tend to degenerate the distribution to the two-layer type with a dense layer below a fresh outflow. The observed distribution of salt is indicative of the balance between the turbulence and this horizontal motion.

Strong vertical turbulence accompanies the tidal current in the Narrows and may completely destroy any vertical salinity gradients during the part of the tidal cycle when horizontal tidal currents are swift. The condition depends to a certain extent on the influx of fresh water. High fresh water run-off may result in stratification being maintained throughout the tidal cycle, as was observed in 1957 March. It must be remembered that the somewhat lower tidal ranges would also have an effect.

The presence of stratification and the form of the distribution of salinity, with the isohalines sloping at high and low water but vertical or near vertical at mid-tide, show that there is a horizontal differential flow between the surface and bottom layers. The estimate of this current difference in Section 5 indicates that it can exceed 37 cm/s even at a time of low fresh-water influx, while the average over a whole tidal cycle will be less.

Pritchard has classified estuarine circulation patterns into four general types (A, B, C and D). Type A is the highly stratified, salt wedge circulation, type B exhibits moderate stratification, having a deep saline inflow and a fresher outflow nearer the surface, while types C and D are vertically homogeneous, but differ from each other in that type C shows marked salinity differences across the estuary and must therefore be fairly wide, whereas a type D estuary has salinity changes only along its length. When considered over one or more tidal cycles the Narrows exhibits type B characteristics. During a tidal cycle, however, the turbulent mixing in this part of the estuary may be so strong that for a period it becomes of type D. A low riverflow aids this transition, whereas a high fresh-water influx and low tidal ranges help to maintain it as a type B estuary.

An extensive programme of sampling for various tidal ranges and riverflows would be necessary to give a full account of the effects of different variables. Observations of velocity should reveal the extent of the surface and bottom layers and give a direct measure of their relative speeds.

8. Acknowledgments

The author is indebted to Professor K. F. Bowden for advice given in the course of carrying out the investigation. He is also grateful to the following authorities without whose assistance the work could not have been undertaken: the Mersey Docks and Harbour Board, the Mersey River Board, and the Cheshire River Board.

Department of Oceanography,
The University,
Liverpoool, 3.
1958 *June* 2

References

Ellison, T. H., 1957. Unpublished MS.
Pritchard, D. W., 1955. *Proc. Amer. Soc. Civ. Eng.*, **81,** separate No. 717.
Proudman, J., 1953. *Dynamical Oceanography*, p. 101, Methuen.
Stommel, H., 1953. *Sewage and Industrial Wastes*, **25**, 9.
Taylor, G. I., 1954. *Proc. Roy. Soc. A*, **223,** 446.
Water Pollution Research Technical Paper No. 7, 1938. H.M.S.O.

On the Chemical Composition of the Outer Core*

Gordon J. F. MacDonald and Leon Knopoff

(Received 1958 August 6)

Summary

The average composition of the Earth is assumed to be the same as that of the chondritic meteorites. This assumption is consistent with the present rate of heat production in the Earth. A core made up solely of iron-nickel is inconsistent with the chondritic model unless the ratio of the abundances of (Fe+Mg)/Si is unity in the mantle. The condition (Fe+Mg)/Si = 1 requires that a major part of the mantle be made of material having the composition of pyroxene or pyroxene-garnet (eclogite). If the mantle is assumed to be made up of a 400 km shell of the composition of eclogite underlain by a material of dunite composition, the chondritic model requires a core of composition $(Fe, Ni)_{1.6}Si$.

The representative atomic number ($\bar{Z}$) has been introduced to characterize compounds at moderately high pressures. From asymptotic relations in the Thomas–Fermi–Dirac model, a basis is formed for the computation of $\bar{Z}$. Bullen's density distribution gives $\bar{Z}$ for the outer core of about 22. The representative atomic number of $Fe_{1.6}Si$ is 22·8. The composition of the core deduced from equation of state arguments is thus consistent with the chondritic model of the Earth.

The electrical conductivity of $(Fe, Ni)_{1.6}Si$ should be a third to a tenth that of pure iron for conditions obtained in the core. Such a conductivity is consistent with the requirements of the dynamo theory of the magnetic field.

1. Introduction

The outer core of the Earth is generally assumed to be a liquid iron-nickel alloy. The evidence advanced in support of this view includes (1) the existence of iron meteorites, (2) the fact that the density of iron is in general agreement with the density of the core as estimated from seismology and from the theory of the figure of the Earth, and (3) that iron would probably be liquid at the temperatures and pressures of the core while silicate materials would be solid.

The hypothesis of an iron core has not gone unchallenged. Kuhn & Rittman (1941) propose a core made up of undifferentiated solar matter, arguing that an iron core is inconsistent with the relative abundances of the elements. Ramsey (1948, 1949, 1950) suggests that the seismic discontinuity at a depth of 2 900 km represents a phase transition from $(Mg, Fe)_2SiO_4$ in the form of olivine in the

* Publication No. 108, Institute of Geophysics, University of California.

mantle to $(Mg, Fe)_2SiO_4$ in a metallic phase in the core. Birch (1952) critically reviews these suggestions and concludes that the core is principally iron-nickel with minor amounts of silicon and carbon since the apparent density of the core is somewhat less than the expected density of pure iron. The view that the 2 900 km discontinuity is a phase change has many attractive features. However a phase change in a multicomponent system almost certainly will be spread out over a range of pressures. From the sharpness of the 2 900 km discontinuity, a strong argument can be made for a marked change in composition at this depth.

Two classes of observations contain evidence regarding the chemical composition of the Earth. Seismic observations and to a lesser degree magnetic and tidal observations indicate the physical characteristics of the material making up the Earth. The interpretation of these observations in terms of chemical composition depends on the measurement or calculation of equations of state of elements and compounds valid for temperatures up to a few thousand degrees and pressures up to about three million atmospheres. The pressures in the core range from one to three million atmospheres. Equations of state for this pressure region have not been developed; it is customary to resort to interpolation between observations of compression in the laboratory on the one hand and calculation of states of matter at pressures so extreme as to cause complex atomic structures to be degenerate on the other.

Direct chemical observations on the outer layer of the Earth, on meteorites and on the Sun lead to estimates of the chemical composition of the solar system. These estimates can be used to determine the chemical composition of the whole Earth, provided some assumption is made regarding the nature of the chemical fractionation that has taken place in the solar system. The purpose of the present paper is to compare the chemical composition of the core obtained by assuming the Earth has the composition of chondritic meteorites with the composition indicated by seismic observations interpreted in terms of an equation of state interpolated between laboratory data and the solution to the Thomas–Fermi–Dirac equation.

2. Chondritic meteorite model for the Earth

Urey (1952) and his co-workers (Urey & Craig 1953, Suess & Urey 1956) suggest that chondritic meteorites provide a sample of the chemical composition of the solar system. Hamaguchi, Reed & Turkevich (1957) have determined the uranium content of chondrites using neutron activation techniques. Bate, Huizenga & Potratz (1957) have carried out similar studies on thorium. This work combined with Edwards's (1955) determination of the potassium content leads to an estimate of the rate at which heat is produced in chondritic matter.

If the whole Earth is made up of chondritic matter, the heat production should be about $2{\cdot}2 \times 10^{20}$ cal/yr. If the Earth contains a chondritic mantle and a non-radioactive iron core the heat production should be $1{\cdot}5 \times 10^{20}$ cal/yr (see Table 1).

If the average value of the heat flow from the Earth is taken to be $1{\cdot}2 \times 10^{-6}$ cm^{-2}s^{-1} the rate of heat production in the Earth today is $1{\cdot}9 \times 10^{20}$ cal/yr, on the assumption that the Earth is in a thermal steady state. An estimate of the uncertainty in this figure comes from two sources: (1) the estimated value of the heat flow may be in error and (2) the Earth is not in a thermal steady state. Birch (1954) points out that the heat flow measurements fall within the range $(1{\cdot}2 \pm 0{\cdot}4) \times 10^{-6}$ cm^{-2}s^{-1} where we have written the standard error of the measurements listed. The

possible uncertainty in the rate of heat production from this source of inaccuracy is thus $\pm 0{\cdot}6 \times 10^{20}$ cal/yr.

If the diffusivity of the mantle is taken to be 0·03 cgs (Clark 1957), then the time constant for the mantle of the Earth is much greater than the present age of the Earth. We are probably obtaining significant heat flow from only the upper 600 km of the mantle. Thus if the radioactivity is uniformly distributed through the mantle the Earth's heat production is actually much greater than that computed from the

Table 1

Heat Production

U	$1{\cdot}1 \times 10^{-8}$ g/g	
Th	$3{\cdot}8 \times 10^{-8}$ g/g	
K	$8{\cdot}0 \times 10^{-4}$ g/g	
Chondritic Mantle and Iron Core		
U	$3{\cdot}29 \times 10^{19}$ cal/yr	
Th	$3{\cdot}12 \times 10^{19}$	
K	$8{\cdot}86 \times 10^{19}$	Total $1{\cdot}53 \times 10^{20}$ cal/yr
Chondritic Earth		
U	$4{\cdot}82 \times 10^{19}$ cal/yr	
Th	$4{\cdot}56 \times 10^{19}$	
K	$1{\cdot}30 \times 10^{20}$	Total $2{\cdot}23 \times 10^{20}$ cal/yr
Observed heat flow		$(1{\cdot}9 \pm 1{\cdot}0) \times 10^{20}$ cal/yr.

observed heat flow. Birch (1958) shows that the chondritic model requires the concentration of radioactivity in the upper few hundred kilometres of the Earth. In order to avoid melting of the mantle below 400 km, MacDonald (1958) suggests that the mantle above this depth has the preponderance of the radioactivity of the Earth. But this is precisely the region in a more or less thermal steady state with the surface. Hence we conclude the uncertainty for the heat production from this cause cannot be more than about $0{\cdot}4 \times 10^{20}$ cal/yr.

A problem of somewhat greater difficulty is the uncertainty arising from the initial heat distribution in the Earth at the time of its formation. This is of course connected with the problem of the present heating or cooling of the mantle. If we accept the view that the accreting Earth formed cold and has been heating ever since, then we do not have to include this possibility in our calculations of heat source production. On the other hand the opposite alternative of origin may give us a very large term. It does not seem likely that this figure can be greater than $0{\cdot}5 \times 10^{20}$ cal/yr (Jeffreys 1952).

Combining the several uncertainties, the rate of heat production in the Earth can be set at $(1{\cdot}9 \pm 1{\cdot}0) \times 10^{20}$ cal/yr. The uncertainty in the present rate of heat production in the Earth does not allow a distinction between the models of a chondritic mantle and a chondritic Earth. The observed heat flow is consistent with the assumption that the Earth as a whole is of chondritic composition (Hurley 1957, Birch 1958).

Table 2 lists the average composition of chondrites in terms of the number of atoms per 10^6 atoms of silicon. In preparing this table the analysis of Wiik (1956) has been added to those reviewed by Urey and Craig. We neglect Urey and Craig's

separation of chondrites into high and low iron groups. The abundances of elements in the Sun's atmosphere as determined by the Michigan group (Aller 1958) are also listed in Table 2 for comparison.

Table 2

Chondritic and solar abundances of metallic elements in number of atoms per 10^6 Si atoms

Element	Chondrites	Solar atmosphere
Na	$4{\cdot}94\times10^4$	$5{\cdot}03\times10^4$
Mg	$9{\cdot}34\times10^5$	$4{\cdot}80\times10^5$
Al	$7{\cdot}91\times10^4$	$4{\cdot}07\times10^4$
Si	$1{\cdot}00\times10^6$	$1{\cdot}00\times10^6$
P	$4{\cdot}55\times10^3$	$6{\cdot}9\times10^4$
S	$1{\cdot}04\times10^5$	$3{\cdot}7\times10^5$
K	$5{\cdot}94\times10^3$	$2{\cdot}29\times10^3$
Ca	$5{\cdot}52\times10^4$	$6{\cdot}03\times10^4$
Ti	$2{\cdot}27\times10^3$	$2{\cdot}29\times10^3$
Cr	$7{\cdot}70\times10^3$	$2{\cdot}51\times10^4$
Mn	$5{\cdot}64\times10^3$	$5{\cdot}30\times10^3$
Fe	$7{\cdot}12\times10^5$	$1{\cdot}45\times10^5$
Co	$2{\cdot}21\times10^3$	$7{\cdot}5\times10^3$
Ni	$3{\cdot}64\times10^4$	$1{\cdot}59\times10^4$

The data of Table 2 can be used to illustrate the inconsistency of assuming a mantle made up largely of olivine and a core of iron and assuming a chondritic Earth. The three principal metals in chondrites and in the Sun are silicon, iron, and magnesium. If we assume a mantle made up of olivine $(Mg_{0{\cdot}9}Fe_{0{\cdot}1})_2SiO_4$ and a core of iron–nickel, the ratio of the sum of the iron, magnesium and nickel abundances to that of silicon is 3·2 as compared to the chondritic ratio of 1·65 (Table 3). A similar contradiction arises if we assume the mantle is a peridotite.

Table 3

Atomic ratios of iron, magnesium and silicon in various earth models

Model		(Fe+Mg+Ni)/Si for whole Earth	Fe/Mg for whole Earth
Composition of Mantle	Composition of Core		
$(Mg_{0{\cdot}9}Fe_{0{\cdot}1})_2SiO_4$	$(Fe_{15}Ni)$	3·2	0·78
$(Mg_{0{\cdot}9}Fe_{0{\cdot}1})SiO_3$	$(Fe_{15}Ni)$	2·2	1·04
Peridotite	$(Fe_{15}Ni)$	2·9	1·3
Chondritic meteorites		1·65	0·71
Solar atmosphere		0·71	0·30

If we assume the mantle is made up of peridotite having the composition given by Daly (1942) (Table 3) and we assume an iron–nickel core, the abundance ratio (Fe+Ni+Mg)/Si for the earth as a whole is 2·9. Maintaining the hypothesis that chondrites are representative chemical samples of the solar system we are left with several possibilities: (1) the composition of the mantle, or core, or both

assumed above is incorrect; (2) some process of differentiation may have concentrated iron and magnesium relative to silicon during the Earth's formation, at the same time keeping the concentration of radioactive elements constant. Ruling out the second hypothesis as too restrictive, we examine alternative compositions for the core and mantle.

An iron core is consistent with a chondritic composition for the Earth, provided the ratio (Fe+Mg)/Si in the mantle is about unity, as illustrated in Table 3. This implies a mantle dominantly of pyroxene composition. The seismic velocities observed in the upper mantle rule out enstatite ($MgSiO_3$) or hypersthene ($Mg_{0.9}Fe_{0.1}$)SiO_3 as major constituents since the quantity $(\partial P/\partial\rho)_S = \phi$ for these minerals (Table 4) is much lower than that observed at depths of 200 to 400 km

Table 4

	Values of $(K_T/\rho)_0$	(K_S/ρ)
Enstatite $MgSiO_3$	29	
Hypersthene $(Mg,Fe)SiO_3$	28	
Forsterite Mg_2SiO_4	36	
100 km depth in Earth		36·8
200 km		40·1
300 km		43·2
400 km		47·0

(Birch 1952). It is possible that pyroxenes undergo a phase transition to a form with higher ϕ at pressures less than those corresponding to depths of 100–200 km but this transition has not been observed experimentally (MacDonald 1957). A mixture of iron-poor pyroxenes and garnets (eclogite) may give a suitable value of ϕ for the upper mantle (Birch 1952).

On the basis of the solid nature of the upper mantle, MacDonald (1958) shows that the radioactive elements must be concentrated in, at most, the upper 400 km of the mantle. Assuming that Na and Al are concentrated along with K, U, and Th in this region the material of the upper 400 km of the mantle would have the composition of an olivine gabbro or eclogite with seismic velocities requiring a mineral assemblage of olivine, magnesium-rich garnet and alkali-rich pyroxene. Assuming an upper mantle (400 km) of eclogite of composition given in Table 5 and a lower mantle of dunite, an iron core leads to a (Fe+Mg)/Si ratio for the Earth of 2·9, and Fe/Mg ratio of 0·94, both values in disagreement with the chondritic ratios.

A chondritic model containing an upper mantle of eclogite and a lower mantle of dunite requires a core having a composition $(Fe, Ni)_{1.6}Si$. The iron–magnesium ratio in such a model is Fe/Mg = 0·71. The ratio of iron to silicon in the core is raised, of course, if a higher silicon content is assumed for the mantle. The composition of the core is not uniquely determined by abundance arguments because of the uncertain composition of the mantle. We do conclude that a core composition of $(Fe, Ni)_{1.6-2.0}Si$ is consistent with the chondritic model for the Earth and with a eclogite–dunite model for the mantle. If a major part of the mantle has the composition of eclogite with $(Fe+Mg)/Si \simeq 1$, the amount of silicon required for the core is reduced in proportion to the ratio of pyroxene–garnet to olivine. Such a model for the mantle is inconsistent with a pure iron core as

is any model for the mantle in which the (Fe + Mg)/Si ratio in the mantle is appreciably greater than one. An iron–nickel–silicon alloy cannot be ruled out on chemical relations observed at one atmosphere, since iron and silicon are completely miscible in the liquid state and even in the solid phase the solubility of silicon in iron ranges from $Fe_{3.1}Si$ at 1 000 °C to $Fe_{3.8}Si$ at 400 °C (Greines, Marsh & Staughton 1933; Farquhar, Lipson & Weill 1945).

Table 5

Composition of possible components of mantle in number of atoms per 10^6 atoms of Si

	eclogite[1]	peridotite[2]	dunite[2]
Na	$5{\cdot}82 \times 10^4$	$2{\cdot}78 \times 10^4$	$2{\cdot}39 \times 10^3$
Mg	$4{\cdot}44 \times 10^5$	$1{\cdot}25 \times 10^6$	$1{\cdot}70 \times 10^6$
Al	$2{\cdot}54 \times 10^5$	$1{\cdot}29 \times 10^5$	$2{\cdot}50 \times 10^4$
Si	$1{\cdot}00 \times 10^6$	$1{\cdot}00 \times 10^6$	$1{\cdot}00 \times 10^6$
P	$1{\cdot}46 \times 10^3$	$1{\cdot}92 \times 10^3$	$5{\cdot}22 \times 10^3$
K	$1{\cdot}49 \times 10^4$	$7{\cdot}10 \times 10^3$	$6{\cdot}29 \times 10^3$
Ca	$2{\cdot}21 \times 10^5$	$8{\cdot}70 \times 10^4$	$1{\cdot}85 \times 10^4$
Ti	$1{\cdot}36 \times 10^4$	$1{\cdot}71 \times 10^3$	$3{\cdot}71 \times 10^3$
Cr	$1{\cdot}36 \times 10^3$	—	—
Mn	$3{\cdot}29 \times 10^3$	$3{\cdot}66 \times 10^3$	$3{\cdot}34 \times 10^3$
Fe	$2{\cdot}41 \times 10^5$	$1{\cdot}58 \times 10^5$	$1{\cdot}67 \times 10^5$
Ni	$6{\cdot}94 \times 10^2$	—	—

[1] Average of 11 non-kyanite bearing eclogites found as inclusions in kimberlite pipes in South Africa (Williams 1932).
[2] After Daly (1942).

3. Calculation of the representative atomic number

Various attempts have been made to apply the Thomas–Fermi equation of state to elements at conditions prevailing in the core (Jensen 1938, Elsasser 1951, Knopoff & Uffen 1954). Marshak & Bethe (1940) indicate the solution to the Thomas–Fermi equation for compounds. Knopoff and Uffen show that the solution to the Thomas–Fermi–Dirac (T.F.D.) equation for compounds simplifies if the compound is characterized by a single "representative atomic number" (Z) which is a weighted mean atomic number for the compound. The equation of state for the compound is the T.F.D. equation of a pure element having the Z of the compound. No difficulty results if the Z assumes non-integer values. The Z is calculated at pressures at which the T.F.D. equation applies but the number is associated with the compound in the intermediate pressure range. We will use the T.F.D. equation to obtain the expression for Z in terms of the atomic number of the constituent elements. The actual equation of state applied to the core is an interpolation between the Birch–Murnaghan equation applicable at pressures up to at least $0{\cdot}5 \times 10^6$ atm (Duvall & Zwolinsky 1955) and the T.F.D. equation applicable at 10^7 atm and higher.

Knopoff and Uffen calculated Z by numerically comparing equations of state of assemblages of elements with the equation of state of pure elements. March (1955) and Gilvarry (1957) present asymptotic solutions to the T.F.D. equation which suggest that the calculation of Z can proceed analytically rather than semi-empirically, provided the calculation is carried out at pressures sufficiently high for the asymptotic solution to hold. These pressures are somewhat greater than

the lowest pressures at which the T.F.D. model is assumed valid, that is to say 10^7 atm. The asymptotic formula accurately represents the equation of state of elements at pressures of 10^9 atm and greater.

Neglecting binding energies and assuming the equality of mass of proton and neutron, the equation of state valid at extreme pressures and absolute zero is

$$\rho = \left(\frac{P}{\alpha}\right)^{3/5}\left(\frac{M}{Z}\right)\left\{1 + \tfrac{3}{5}\beta Z^{2/3}\left(\frac{P}{\alpha}\right)^{-1/5} + \tfrac{3}{5}\gamma\left(\frac{P}{\alpha}\right)^{-1/5}\right\}$$

where

P = pressure
Z = atomic number
M = atomic weight
ρ = density
$\alpha = (3\pi/8)^{2/3}(\eta^5 m^8)^{1/3}h^2/5$
$\beta = 2\pi e^2(4\eta m^4)^{1/3}h^{-2}$
$\gamma = 5(\pi\eta m/3)^{1/3}(e/h)^2$
h = Planck's constant
e = electronic charge
m = mass of the electron
η = ratio of mass of proton to mass of electron.

We consider a compound Y with a chemical formula

$$X_{n_1}{}^1\ X_{n_2}{}^2 \ldots X_{n_m}{}^m$$

where the n_i are the number of atoms of the element X^i in the chemical formula. The condition that a compound with representative atomic number $\bar{Z}$ and representative atomic weight $\bar{M}$ has the same density as Y is then

$$(\bar{M}/\bar{Z})(P/\alpha)^{3/5}\{1 + \tfrac{3}{5}\beta\bar{Z}^{2/3}(P/\alpha)^{-1/5} + \tfrac{3}{5}\gamma(P/\alpha)^{-1/5}\} = \frac{\sum_i n_i M_i}{\sum_i n_i Z_i (P/\alpha)^{-3/5}\{1 + \tfrac{3}{5}\beta Z_i^{2/3}(P/\alpha)^{-1/5} + \tfrac{3}{5}\gamma(P/\alpha)^{-1/5}\}^{-1}} \tag{1}$$

where Z_i is the atomic number of element $X^{(i)}$, M_i is the atomic weight of element $X^{(i)}$.

We now make the assumption that the abundance of neutrons in our hypothetical compound with representative atomic number $\bar{Z}$ is determined by the actual abundance of neutrons in compound Y. We state that the ratio of neutrons to protons in both Y and in the equivalent compound is the same.

$$\frac{\sum_{i=1}^{m} n_i M_i}{\sum_{i=1}^{m} n_i Z_i} = \frac{\bar{M}}{\bar{Z}}. \tag{2}$$

Combining equations (1) and (2) we obtain an expression for $\bar{Z}$, viz:

$$\bar{Z}^{2/3} = \frac{\sum_{i=1}^{m} n_i Z_i^{5/3}}{\sum_{i=1}^{m} n_i Z_i}.$$

Representative values of Z for various materials are listed in Table 6. The impressive feature of the values listed in Table 6 is that Z for all silicates and for all oxides except those of iron is well below 20.

Table 6

Representative atomic numbers of compounds

Material	Formula	Z
Quartz	SiO_2	10.7
Anorthite	$CaAl_2Si_2O_8$	11.7
Orthoclase	$KAlSi_3O_8$	11.6
Albite	$NaAlSi_3O_8$	10.6
Diopside	$CaMgSi_2O_6$	12.0
Enstatite	$MgSiO_3$	10·5
Jadeite	$NaAlSi_2O_6$	10·5
Fayalite	Fe_2SiO_4	17·7
Forsterite	Mg_2SiO_4	10·5
Andradite	$Ca_3Fe_2(SiO_4)_3$	15·1
Grossularite	$Ca_3Al_2(SiO_4)_3$	12·6
Almandite	$Fe_3Al_2(SiO_4)_3$	14·8
Pyrope	$Mg_3Al_2(SiO_4)_3$	11·7
Spodumene	$LiAlSi_2O_6$	10·2
Beryl	$Be_3Al_2Si_6O_{18}$	10·0
Corundum	Al_2O_3	10·4
Wustite	FeO	21·2
Magnetite	Fe_3O_4	20·1
Hematite	Fe_2O_3	19·6
Periclase	MgO	10·3
Spinel	$MgAl_2O_4$	10·5
Rutile	TiO_2	15·5
Oldhamite	CaS	18·2
Troilite	FeS	22·0
Pyrite	FeS_2	20·3
Galena	PbS	69·0
Sphalerite	ZnS	24·8
Iron	Fe	26
Nickel	Ni	28
	Fe_2Si	23·2
	$Fe_{1.6}Si$	22·8

4. Chemical composition of the core derived from seismology and equation of state arguments

On the basis of Bullen's density distribution, various workers infer that the outer core is somewhat less dense than pure iron or an iron–nickel alloy (Birch 1952, Bullen 1952). Knopoff and Uffen, using an interpolated equation of state, obtain a Z for the outer core of 22. The exact value of Z is uncertain because of the nature of the interpolation and the small but unknown effect of temperature on the equation of state. It appears unlikely that the uncertainty could be as great as four units in Z but might be as large as one or two units. We will use a value of 22 for Z for the outer core. Since the atomic numbers of iron and nickel are 26 and 28 respectively, some lighter elements must be present in the core in order to bring Z down to 22.

The abundance arguments reviewed above suggest that silicon might be a major constituent of the Earth's core. In Figure 1 we show the dependence of Z

for a solution of iron and silicon on the amount of silicon present. If Z for the core lies between 22 and 23, then the outer core must contain between 20 and 30 weight per cent silicon corresponding to the formulae $Fe_{1.2}Si$($Z = 22$) and $Fe_{2.1}Si$ ($Z = 23$) respectively. The composition of $Fe_{1.6}Si$ suggested by the abundance of elements is thus in excellent agreement with the composition deduced on the basis of equations of state, provided silicon is assumed to be the alloying element. The equation of state cannot rule out the possibility of a liquid solution of Fe–Si–Mg. Figure 2 gives the relations between the number of atoms of these

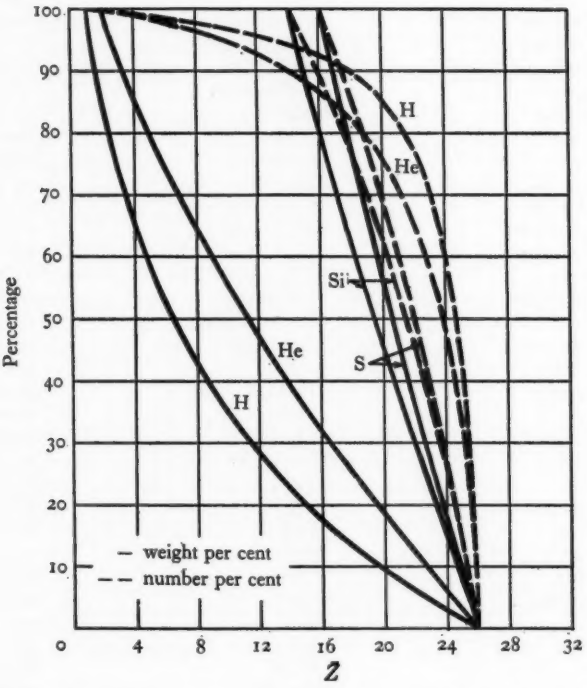


FIG. 1.—The number per cent of atoms and the weight per cent of elements required to dilute iron to a given value of $\bar{Z}$ for the systems Fe_xH_y, Fe_xHe_y, Fe_xSi_y, Fe_xS_y.

three constituents and Z. Since silicon and magnesium have atomic numbers which are close to one another, we see that the range $Fe_{1.2}$(Si, Mg) to $Fe_{2.1}$(Si, Mg) fits estimates of Z. Similarly nickel and iron have similar atomic numbers and solutions of the form $(Fe, Ni)_{1.2}Si$ to $(Fe, Ni)_{2.1}Si$ fit the requirements of the equation of state. The abundance of Ni in chondrites suggests a Fe/Ni ratio of about 20.

The limits imposed by the estimated values of $\bar{Z}$ do not uniquely determine the composition of the core. Other elements and combination of elements can be used to reduce the atomic number of the material in the core as is illustrated in Figure 1. Solar and chondritic abundances suggest that hydrogen, helium, carbon, oxygen, nitrogen, magnesium and sulphur are likely candidates for reducing the value of Z of the core. All but magnesium are either highly volatile or form highly volatile compounds under a wide range of conditions. If we consider chondritic meteorites

as indicating those elements other than silicon that might be retained by a planet in large quantities then only oxygen, magnesium and sulphur are possible diluents of iron–nickel.

Any high-pressure modification of a silicate material is ruled out as the sole constituent of the outer core, since the $\bar{Z}$ values for silicates are all considerably lower than 22. A mixture of magnesium silicate and metallic iron is a possibility. If such a silicate were initially dispersed in a molten iron core it would almost certainly gravitate towards the outer edge of the core and merge with material of the mantle. Alternatively, the silicate material might be liquid. In this case we would have to assume that the metal phase and silicate phase were miscible, otherwise these two phases would tend to separate under gravity into a region of high $\bar{Z}$

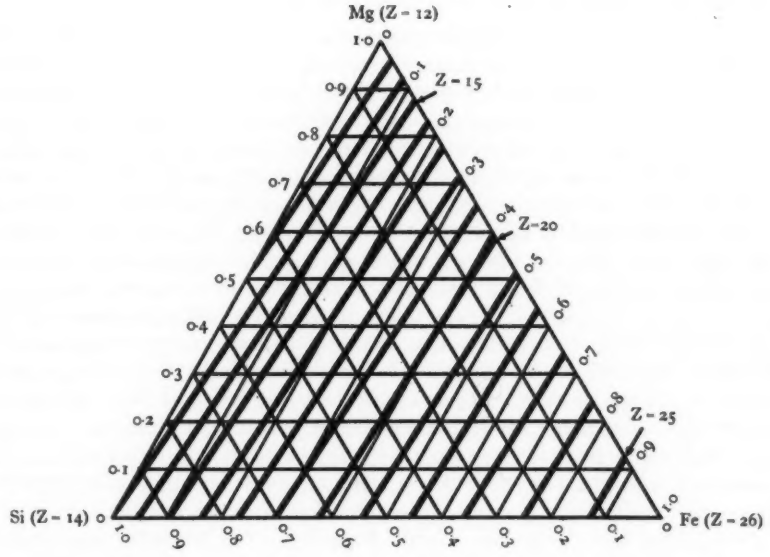


FIG. 2.—The fraction of number of atoms for different values of $\bar{Z}$ in the system $Fe_xMg_ySi_z$.

below a region at the top of the core of lower $\bar{Z}$. Such a liquid separation in the outer core contradicts the seismic evidence. Molten silicates and metallic iron are immiscible at surface pressures; there is no reason to expect a marked increase of solubility at core conditions.

As is evident from Figure 1, a large number of atoms but only a small weight of either hydrogen or helium reduces $\bar{Z}$ for the core to the range of 22–23. Both of these elements are abundant in the Sun but are not major constituents of meteorites. There is no guarantee that the present gaseous composition of meteorites in any way represents their original volatile element composition so that hydrogen and helium remain possible if perhaps unlikely diluents of the core.

Sulphur is a possible major component of the core since FeS has a $\bar{Z}$ of 22. Iron sulphide is found in meteorites as troilite. The abundance of sulphur in chondrites is about a tenth that of silicon. If the core were FeS and the mantle

were eclogite–dunite with no sulphides, then the ratio of sulphur to silicon would be S/Si = 0·77 rather than 0·1 or 0·37 as indicated by chondritic and solar abundances respectively. A postulate of an iron–sulphur mixture with the appropriate Z for the core requires an initial high abundance of sulphur or some process by which silicon is lost to the Earth with respect to sulphur. Neither of these hypotheses seems probable though they cannot be ruled out completely. On the chondritic model of the Earth it is possible to account for the sulphur by 3 to 4 per cent by weight of metallic sulphides in the mantle with the remaining sulphur in the core. However sulphur cannot be ruled out as a possible component of the core though quantitatively the abundance of available sulphur is too low for it to be the major diluent of the core.

5. Problems raised by a core of iron silicide

We have shown that a core of composition $(Fe, Ni)_{1.6}Si$ is consistent with a chondritic composition for the Earth, provided the mantle is made up of an upper layer having the composition of eclogite and a lower shell of dunite composition. The Z of $Fe_{1.6}Si$ is 22·8 while that calculated for the core from Bullen's density data is 22. The agreement between two methods of estimating the composition of the core may be fortuitous. Since the agreement is sufficiently striking we examine two of the problems raised by the postulate of a core containing abundant silicon.

The dynamo theories of the Earth's magnetic field require a material of relatively high electrical conductivity in the core. Runcorn (1956) on the basis of the form of the secular variation spectrum derives a value of $10\,\text{ohm}^{-1}\,\text{cm}^{-1}$ as the conductivity of the core. The analysis by Bullard, Freedman, Gellman & Nixon (1950) of the westward drift shows that a value of $3 \times 10^3\,\text{ohm}^{-1}\,\text{cm}^{-1}$ is a reasonable estimate of the conductivity and it is this latter value that is generally used in discussions of the theory of the magnetic field. Various attempts have been made to estimate the conductivity of iron at conditions prevailing in the core. Elsasser's (1950) estimate is $1{\cdot}3 \times 10^4\,\text{ohm}^{-1}\,\text{cm}^{-1}$ for iron at 9 000 °C or 3×10^4 at a more reasonable temperature of 4 000 °C. A conductivity as high as $3 \times 10^4\,\text{ohm}^{-1}\text{cm}^{-1}$ requires that the currents producing the time-dependent part of the field originate in a very thin layer near the mantle boundary. The electrical and magnetic properties of iron–silicon alloys at surface conditions are well known because of the use of iron–silicon alloys as transformer cores and in other electrical equipment. The conductivity of pure iron ($1 \times 10^5\,\text{ohm}^{-1}\,\text{cm}^{-1}$) decreases markedly with the addition of silicon to the value of $1 \times 10^4\,\text{ohm}^{-1}\,\text{cm}^{-1}$ at 11 per cent silicon by weight. At 14·5 per cent silicon the conductivity reaches a maximum of $3 \times 10^4\,\text{ohm}^{-1}\,\text{cm}^{-1}$ and decreases with further addition of silicon (Bozorth 1951). The extrapolation of these conductivity values to conditions of the core is most uncertain but it seems likely that the conductivity of $Fe_{1.6}Si$ would be lower than that of pure iron by a factor of three and perhaps lower by an order of magnitude. Both theory and "observations" require a conductivity somewhat less than that estimated for pure iron so that a core composition of $Fe_{1.6}Si$ is consistent with what is presently known about the Earth's magnetic field.

The existence of iron meteorites free of iron silicide suggests a further problem. The hypothesis of an iron–silicon core requires that the process by which iron is freed from oxygen in the Earth differ from the mechanism by which free iron is produced in meteorites. The closeness of the ratio of iron to silicon in the postulated core and in the mineral fayalite provides the tantalizing suggestion that the core is produced by the squeezing of oxygen out of a silicate having a composition

Fe_2SiO_4. A requirement for such a process is that the system be open to oxygen so that the volume change in the reaction $Fe_2SiO_4 = Fe_2Si + 2O_2$ is solely the difference in volume of Fe_2Si and Fe_2SiO_4. A convective process sweeping away the volatile components might provide the mechanism by which the system is opened to oxygen. At zero oxygen pressure $Fe_2Si + 2O_2$ is stable relative to Fe_2SiO_4 as measured by the heat of formation of Fe_2SiO_4. Neglecting the changes of entropy and volume with temperature and pressure, the change in the Gibbs free energy in the reaction

$$Fe_2SiO_4 = Fe_2Si + 2O_2$$

at high total pressure is

$$\Delta G = \Delta G_0 + P\Delta V_s - (T - T_0)\Delta S$$

where ΔG_0 is the change in the Gibbs free energy for the reaction at surface conditions, ΔV_s is the difference in the volumes of the solid phases and ΔS is the total change of entropy. Assuming a partial pressure of oxygen of 1 atm and standard thermochemical data (Kubaschewski & Evans 1951) the pressure needed to convert Fe_2SiO_4 into Fe_2Si plus oxygen is of the order of 7×10^5 atm while 5×10^6 atm are needed to squeeze oxygen out of forsterite under the same conditions. These calculations neglect the effect of the possible phase changes of olivine to spinel but since the surface oxygen pressure is of the order of 1 atm they indicate the *minimum* pressures required to break down iron silicates. These pressures are reached within the Earth but probably not in the planet from which the meteorites may have been derived.

The suggestion that the outer core be a silicide has also been made by Ringwood (in press). Ringwood has approached the problem from the point of view that the solar matter undergoes progressively greater chemical reduction in depth in the Earth. Although the general conclusions are similar the process of introducing a silicide into the core is different; Ringwood suggests an amount of silicon similar to that proposed here.

Institute of Geophysics,
University of California,
Los Angeles,
Cal., U.S.A.
1958 *May* 23

References

Aller, L., 1958. The Abundances of the Elements in the Sun and Stars, *Handbuch der Physik*, Part X, v. 2.

Bate, G. L., Huizenga, J. R. & Potratz, H. A., 1957. Thorium Content of Stone Meteorites, *Science*, **126**, 612–614.

Birch, F., 1952. Elasticity and Constitution of the Earth's Interior, *J. Geophys. Res.* **57**, 227–286.

Birch, F., 1954. The Present State of Geothermal Investigations, *Geophysics*, **19**, 645–659.

Birch, F., 1958. Differentiation of the Mantle, *Bull. Geol. Soc. Amer.*, **69**, 483–486.

Bozorth, R. M., 1951. *Ferromagnetism* (D. van Nostrand, New York).

Bullard, E. C., Freedman, C., Gellman, H. & Nixon, J., 1950. The Westward Drift of the Earth's Magnetic Field, *Phil. Trans. Roy. Soc. A.* **243,** 67–92.

Bullen, K. E., 1952. On Density and Compressibility at Pressures up to Thirty Million Atmospheres. *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **6,** 383–401.

Clark, S. P., 1957. Radiative Transfer in the Earth's Mantle. *Trans. Amer. Geophys. Un.*,**38,** 931–938.

Daly, R. A., 1942. *Composition of Igneous Rocks*, in Handbook of Physical Constants, ed. Birch, Schairer and Spicer, Geol. Soc. Amer. Special Paper, No. 36, 2.

Duvall, G. E. & Zwolinsky, B. J., 1955. Entropic Equations of State and Their Application to Shock Wave Phenomena in Solids, *J. Acoust. Soc. Amer.*, **27,** 1054–1058.

Edwards, G., 1955. Sodium and Potassium in Meteorites, *Geochim. et Cosmochim. Acta*, **8,** 285–294.

Elsasser, W. M., 1950. The Earth's Interior and Geomagnetism, *Rev. Mod. Phys.*, **22,** 1–35.

Elsasser, W. M., 1951. Quantum Theoretical Densities of Solids at Extreme Compression, *Science*, **113,** 105–107.

Farquhar, M., Lipson, H. & Weill, **A.**, 1945. An X-ray Study of Iron-Rich Iron Silicon Alloys, *J. Iron Steel Inst.*, **152,** 457–470.

Gilvarry, J. J., 1957. Asymptotic Relations in the Thomas–Fermi–Dirac Atom Model, *J. Chem. Phys.*, **27,** 150–154.

Greiner, E. S., Marsh, J. S. & Staughton, B., 1933. *Alloys of Iron and Silicon*, (McGraw-Hill, New York).

Hamaguchi, H., Reed, G. W. & Turkevich, A., 1957. Uranium and Barium in Stone Meteorites, *Geochim. et Cosmochim. Acta*, **12,** 337–347.

Hurley, P. M., 1957. Test on the Possible Chondritic Composition of the Earth's Mantle and Its Abundance of Uranium, Thorium and Potassium, *Bull. Geol. Soc. Amer.*, **68,** 379–382.

Jensen, H., 1938. Das Druck-Dichte Diagramm der Elements bei hoheren Drucken um Temperaturnullpunkt. *Z. Physik*, **111,** 373–385.

Knopoff, L. & Uffen, R. J., 1954. The Density of Compounds at High Pressures and the State of the Earth's Interior, *J. Geophys. Res.* **59,** 471–484.

Kubaschewski, O. & Evans, E., 1951. *Metallurgical Thermochemistry* (Butterworth-Springer, London) 368 pp.

Kuhn, W. & Rittmann, A., 1941. Uber den Zustand des Erdinnern und seine Enstehung aus einem Homogenen Urzustand. *Geol. Rundschau*, **32,** 215–256.

MacDonald, G. J. F., 1957. Quartz-Coesite Stability Relation at High Temperatures and Pressures. *Amer. J. Sci.*, **254,** 713–721.

MacDonald, G. J. F., 1958. Chondrites and the Chemical Composition of the Earth. *Research in Geochemistry*, ed. P. H. Abelson (J. Wiley, New York).

March, N. H., 1955. Equations of State of Elements from the Thomas–Fermi Theory, *Proc. Phys. Soc. A.*, **68,** 726–734.

Marshak, R. E. & Bethe, H. A., 1940. The Generalized Thomas–Fermi Method as Applied to Stars, *Astrophys. J.*, **91,** 239–243.

Ramsey, W. H., 1948. On the Constitution of the Terrestrial Planets, *Mon. Not. R. Astr. Soc.*, **108,** 406–413.

Ramsey, W. H., 1949. On the Nature of the Earth's Core, *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **5,** 409–426.

Ramsey, W. H., 1950. On the Compressibility of the Earth, *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **6**, 42–49.

Ringwood, A. E., *In Press*, On the Chemical Evolution and Densities of the Planets.

Runcorn, S. K., 1956. The Magnetism of the Earth's Body, *Handbuch der Physik*, **48**, 498–533.

Suess, H. & Urey, H. C., 1956. Abundances of the Elements, *Rev. Mod. Phys.*, **28**, 53–74.

Urey, H. C., 1952. *The Planets* (Yale University Press, New Haven).

Urey, H. C. & Craig, H., 1953. The Composition of the Stone Meteorites and The Origin of Meteorites, *Geochim. et Cosmochim. Acta*, **4**, 36–82.

Wiik, H. B., 1956. Chemical Composition of Some Stony Meteorites, *Geochim. et Cosmochim. Acta*, **9**, 279–289.

Williams, A. F., 1932. *The Genesis of the Diamond* (E. Benn, London, Vol. 1).

A New Determination of the Differences in Gravity between the N.P.L. Teddington and the South African Fundamental and Secondary Stations

D. I. Gough*

(Received 1958 July 10)

Summary

Observations have been made with the Cambridge pendulum apparatus at the British Fundamental gravity station at the N.P.L. Teddington, at the South African Fundamental gravity station at Johannesburg,† and at the South African secondary stations at Pretoria and Mowbray. Two pendulums were exposed to mercury during the project. The remaining four, namely I A, I B, I C and VI A, give for the mean gravity differences

Teddington–Mowbray	$= 1{\cdot}5495 \pm 0{\cdot}0001$ cm/s^2
Teddington–Johannesburg	$= 2{\cdot}6472 \pm 0{\cdot}0003$ cm/s^2
Teddington–Pretoria	$= 2{\cdot}5672 \pm 0{\cdot}0003$ cm/s^2

whence, adopting g = 981·1963 cm/s^2 at Teddington,
g = 979·6468 cm/s^2 at Mowbray
978·5491 at Johannesburg
978·6291 at Pretoria.

These values agree well with the determinations of 1948–9 by Hales and Gough.

1. Introduction

The gravity survey of the Union of South Africa has recently been completed with the publication by the Union Geological Survey of a Bouguer anomaly map‡ overprinted on the 1 : 1 M geological map of the Union. The gravity map represents gravity meter observations at about 6 300 stations. The gravity meter observations were controlled by the primary network of pendulum stations, forty in the Union and thirteen in neighbouring territories, observed by Hales and Gough in 1948–9 using the Cambridge invar pendulums (Hales & Gough 1950). The pendulum stations in Southern Africa were occupied in loops beginning and ending at the Fundamental station at the Bernard Price Institute of Geophysical Research, Johannesburg, or at the Trigonometrical Survey Office, Mowbray, Cape Town. In consequence, measurements were made several times during the pendulum

* National Physical Research Laboratory, Council for Scientific and Industrial Research, Pretoria.

† No formal decision has been taken that Johannesburg shall be the South African Fundamental Station, but it is the South African first order station in the international network.

‡ This map may be purchased from the Government Printer, Pretoria.

survey at each of these stations, and the difference in gravity between Cambridge and each of them was well determined. A re-connexion between Mowbray and Johannesburg and a first-order station in another continent is therefore equivalent to a re-connexion between the national survey and the international gravity network.

In addition to the general desirability of a new determination of the differences between the British Fundamental station at the National Physical Laboratory, Teddington, and the South African stations, there was a specific reason for a new connexion. This was the uncertainty regarding the effects of magnetic interaction between the invar pendulums and the geomagnetic field, or between the pendulums and the mu-metal shield with which the pendulum swinging case was lined during the 1948–9 work (Bullard 1933, Cook 1954). This uncertainty was increased by the reversal of the vertical component of the geomagnetic field between Britain and South Africa. Further, the Cambridge pendulums have on various occasions shown small discrepancies in the measured gravity differences given by Set I and Set VI respectively (Cook 1954) and this discrepancy was exceptionally large for the 1948–9 survey (Hales & Gough 1950, Cook 1957). Cook has advanced an explanation of this discrepancy based on magnetic perturbation (Cook 1954).

For these reasons the writer accepted with pleasure an offer by Mr B. C. Browne to make the Cambridge pendulum apparatus available for a new connexion between Teddington and the South African stations. Mr J. E. Jackson and the writer made the initial observations at Teddington and the apparatus travelled to Cape Town in the writer's care. After the South African observations had been completed, the apparatus was shipped to Southampton and Mr Browne made the closing observations at Teddington.

2. Measurement procedure

The positions of the South African stations are given in Table 1. It will be seen that measurements were made at the Transvaal Museum, Pretoria, station

Table 1

Positions of stations in S. Africa

Designation	Description	Latitude S	Longitude E	Height (m)
Mowbray	Trigonometrical Survey Office, Mowbray, Cape Town	33°57′·1	18°28′·1	38·4
Johannesburg	Bernard Price Institute, Johannesburg.	26°11′·5	28°01′·8	1755·0
Pretoria	Transvaal Museum, Pretoria	25°45′·1	28°11′·4	1337·1

as well as at Mowbray and Johannesburg. These were made because the gravity meter network of the gravity survey used Pretoria as origin. The stations were

observed in the sequence Teddington–Mowbray–Johannesburg–Pretoria (two sets of observations)—Johannesburg–Mowbray–Teddington.

The Cambridge pendulum apparatus has been described frequently (see Browne, Cook, McCarthy & Parasnis 1950 for references). Two invar pendulums of half-period slightly greater than 0·5 s were swung in antiphase about an axis which was along the magnetic meridian. The mu-metal lining formerly used to reduce the field within the swinging case had been removed, and instead a Helmholtz pair of coils annulled the vertical component of the geomagnetic field. The pendulum periods were measured by comparison with a clock driven by a quartz crystal oscillator of frequency about 100 000 c/s, light signals from the pendulums and clock being recorded together on a chronograph drum. The air pressure in the swinging case varied from 18·9 to 27·2 mm of mercury, and was measured throughout by one U-tube manometer inside the swinging case, checked through an external connexion against the N.P.L. standard U-tube at Teddington, and against a second manometer in South Africa. At Teddington the quartz oscillator was rated by beating the second harmonic of its output with the 200 kc/s carrier of the B.B.C. Light Programme. For rating the clock in South Africa, Mr L. Flavell of the Department of Geodesy and Geophysics, Cambridge, attached to the clock a cam-operated contact-breaker which enabled the output of a radio receiver to be interrupted once every half-second of clock time. The contact-breaker could be rotated round the axis of the cam and its angular displacement was shown on a dial in hundredths of a half-second of clock time. The device was used with the 5 Mc/s transmission of ZUO, the radio station of the Union Observatory, Johannesburg. This transmission included "ticks" every second consisting of 10 cycles of 1 000 c/s tone. The contact-breaker was turned until the "ticks" just disappeared, the dial was read, and the time was noted. By repeating the setting several times over several hours, the rate of the clock could be found with a precision limited by radio interference, but always in the present work high enough to make error in clock rate negligible compared with the overall variations in pendulum periods. In practice, the contact-breaker was set so that the "tick" just disappeared inside the leading and trailing edges of the silent interval, and the mean of the two dial settings was used, so as to minimize effects of variation in signal to noise ratio and of eccentricity of the contact-breaker. Several such pairs of settings made up an observation.

Both at Teddington and in South Africa rating observations were made at intervals during each day on which pendulums were swung. At Mowbray, radio reception conditions made it necessary to work at night. The rates measured are given in Table 2. Most of the variation in rate resulted from temperature variation.

One set of observations at a station consisted of three swings (in two cases four swings) of each of four pairs of pendulums, the pairs being I A, B; I A, C; VI A, B and VI B, C. In most cases only one pair of pendulums was swung in a day, to give maximum time for settling down of temperature after handling. One swing was about 7 000 half-seconds long, all other swings had duration about 8 000 half-seconds.

Before the first observations at Mowbray an externally connected manometer broke in such a way that mercury was forced into the swinging case by the ingoing air and sprayed over the VI B and VI C pendulums. The mercury droplets did not appear to wet the gold plating, and when the pendulums had been wiped they

Table 2

Rate of quartz oscillator

Date	Pendulums in use	Rate $\times 10^8$	Date	Pendulums in use	Rate $\times 10^8$
	Teddington			*Pretoria*	
20/9/56	VI BC	$+529 \pm 1$	17/11/56	I AB	$+480 \pm 2$
21	VI AB	$+531 \pm 2$	19	I AC	$+480 \pm 4$
21	I AB	$+530 \pm 1$	20	VI AB	$+470 \pm 3$
22	I AB	$+532 \pm 1$	21	VI BC	$+469 \pm 3$
24	I AC	$+525 \pm 1$			
	Mowbray			*Johannesburg*	
19–20/10/56	I AB	$+517 \pm 3$	23/11/56	I AB	$+514 \pm 3$
20–21	I AC	$+509 \pm 6$	26	I AC	$+510 \pm 2$
23–24	VI BC	$+523 \pm 5$	27	VI BC	$+508 \pm 2$
26–27	VI AB	$+535 \pm 5$	28	VI AB	$+506 \pm 2$
	Johannesburg			*Mowbray*	
5–6/11/56	VI BC	$+514 \pm 1$	1–2/12/56	VI BC	$+498 \pm 3$
7	VI AB	$+525 \pm 3$	2–3	VI AB	$+498 \pm 3$
8	I AB	$+520 \pm 2$	3–4	I AB	$+495 \pm 5$
9	I AC	$+502 \pm 4$	4–5	I AC	$+501 \pm 7$
	Pretoria			*Teddington*	
13/11/56	I AC	$+503 \pm 3$	20/2/57	I AB	$+520 \pm 4$
14	I AB	$+489 \pm 4$	21	I AC	$+518$
15	VI BC	$+494 \pm 2$	21	VI AB	$+515 \pm 5$
16	VI AB	$+456 \pm 3$	22	VI BC	$+517 \pm 6$

Note—The errors quoted are mean square errors.

appeared unchanged. During subsequent weeks, however, spots and cloudy areas of amalgam appeared, especially on pendulum VI B.

The usual corrections were applied to yield half-periods at zero amplitude and pressure, 0 °C and zero clock rate. The amplitude correction varied from -143 to -174, the pressure correction from -279 to -369, the temperature correction from -468 to -629 and the clock rate corrections from -231 to -271, all in units of 10^{-8} s as corrections to the pendulum half-period.

3. The observations

The corrected pendulum half-periods are given in Table 3. It will be seen that there appears to be a general tendency for the half-periods of all the pendulums except VI B to increase between the first and second measurements at each station. In particular at Pretoria the mean period for the second set of observations is greater than that for the first set for all six pendulums, the differences in half-period ranging from $+9$ to $+32 \times 10^{-8}$ s. The mean difference is 20×10^{-8} s, corresponding to 0·8 mgal. Between these two sets of observations, which together occupied nine days, the pendulum swinging case was lifted, re-oriented with respect to the magnetic meridian and re-levelled. The pendulums were handled

Table 3

Pendulum Half Periods

Unit 10^{-4} s

Station	Date	IA	IB	IC	VIA	VIB	VIC
Teddington	20–24/9/1956	5062 4814	5062 5092		5054 6259	5054 6360	
		4829	5078		6252	6358	
		4810	5089		6239	6354	
		4823		5062 4783		6418	5054 6151
		4808		4788		6386	6180
		4811		4778		6375	6184
	Mean	5062 4816	5062 5086	5062 4783	5054 6250	5054 6375	5054 6172
	20–22/2/1957	5062 4879	5062 5090		5054 6270	5054 6377	
		4871	5111		6298	6343	
		4875	5101		6293	6353	
		4876		5062 4774		6382	5054 6213
		4863		4813		6372	6219
		4865		4801		6354	6243
	Mean	5062 4872	5062 5101	5062 4796	5054 6287	5054 6364	5054 6225
	Mean of means	**5062 4844**	**5062 5094**	**5062 4790**	**5054 6268**	**5054 6370**	**5054 6198**
Mowbray	19–27/10/1956	5066 4839	5066 5100		5058 6201	5058 6285	
		4848	5112		6211	6288	
		4838	5096		6231	6276	
		4847		5066 4791		6333	5058 6120
		4838		4805		6339	6122
		4849		4834		6334	6110
		4847		4806			
	Mean	5066 4842	5066 5103	506 64809	5058 6214	5058 6309	5058 6117
	1–5/12/1956	5066 4874	5066 5115		5058 6252	5058 6278	
		4889	5121		6240	6292	
		4877	5124		6255	6284	
		4881		5066 4818		6305	5058 6163
		4881		4816		6299	6146
		4886		4801		6309	6144
	Mean	5066 4881	5066 5120	5066 4812	5058 6249	5058 6294	5058 6151
	Mean of means	**5066 4862**	**5066 5112**	**5066 4810**	**5058 6232**	**5058 6302**	**5058 6134**

	Mean of means	**5066 4862**	**5066 5112**	**5066 4810**	**5058 6232**	**5058 6302**	**5058 6134**

d

Unit 10^{-4} s

Station	Date	IA	IB	IC	VIA	VIB	VIC
Johannesburg	5–9/11/1956	5069 3280	5069 3506		5061 4597	5061 4650	
		3278	3504		4597	4657	
		3278	3507		4608	4656	
		3277		5069 3219		4688	5061 4503
		3287		3213		4678	4497
		3291		3225		4689	4502
	Mean	5069 3282	5069 3506	5069 3219	5061 4601	5061 4670	5061 4501
	23–28/11/1956	5069 3291	5069 3519		5061 4591	5061 4653	
		3293	3520		4605	4663	
		3290	3527		4607	4657	
		3291		5069 3220		4680	5061 4513
		3291		3221		4678	4528
		3283		3205		4679	4508
	Mean	5069 3290	5069 3522	5069 3215	5061 4601	5061 4668	5061 4516
	Mean of means	**5069 3286**	**5069 3514**	**5069 3217**	**5061 4601**	**5061 4669**	**5061 4508**
Pretoria	13–16/11/1956	5069 1197	5069 1424				
		1206	1450		5061 2525	5061 2581	
		1191	1443		2535	2580	
		1207	1446		2528	2580	
		1189		5069 1130		2606	5061 2430
		1197		1136		2602	2436
		1177		1122		2613	2435
	Mean	5069 1195	5069 1441	5069 1129	5061 2529	5061 2594	5061 2434
	17–21/11/1956	5069 1217	5069 1449		5061 2555	5061 2593	
		1213	1441		2543	2601	
		1216	1460		2555	2609	
		1215		5069 1141		2620	5061 2461
		1221		1154		2627	2462
		1216		1155		2625	2474
	Mean	5069 1216	5069 1450	5069 1150	5061 2551	5061 2612	5061 2466
	Mean of means	**5069 1206**	**5069 1446**	**5069 1140**	**5061 2540**	**5061 2603**	**5061 2450**

with the usual stringent precautions, and in any case it is unlikely that all six increased in length. The physical conditions associated with corrections changed only slightly. The magnetic moments of the pendulums changed only slightly. Possible levelling errors were far too small to account for the differences. The data suggest that there are unknown effects associated with setting up the swinging case which may cause variations of the order of one milligal. If so, the variation of period between swings of a set with the swinging case undisturbed will not reflect the true precision of a measurement. It might be useful, though tedious, to study the effect by means of a series of sets of swings at some one station.

The closure differences in half-period at Teddington range from $+13$ to $+56 \times 10^{-8}$ s for the four pendulums used in deriving the differences between Teddington and the South African stations. The mean closure difference of $+30 \times 10^{-8}$ s corresponds to 1·2 mgal.

The VI pendulums were swung in pairs VI A, B and VI B, C instead of VI A, B and VI A, C, on the suggestion of Mr Browne, so that the VI B pendulum was used on both left and right pairs of agates, and any change in the difference between the rigidities of the two supports would show as a change in the difference in the half-periods. Part of the difference will be due to sway coupling to VI A and VI C respectively, but this will be constant (Browne & others 1950). Table 4 shows that there was such a difference and that it was apparently not constant.

Table 4

Difference, Δ, of mean half-period of Pendulum VI B on right-hand agate from that on left-hand agate

Station	T	M	J	P	P	J	M	T
$\Delta(10^{-8}$ s)	36	52	31	27	23	21	19	11

The gravity differences from Teddington are given in Table 5. These have been calculated using the equations

$$\Delta g = -3{\cdot}87634 \times 10^{-5}\Delta T + 1{\cdot}149 \times 10^{-12}(\Delta T)^2$$

for the set I and

$$\Delta g = -3{\cdot}88237 \times 10^{-5}\Delta T + 1{\cdot}152 \times 10^{-12}(\Delta T)^2$$

for the set VI. Gravity differences are given for each of the six pendulums. Mean differences are quoted for all six pendulums, and for I A, I B, I C and VI A. It is the writer's view that the latter should be adopted in view of the accident with the mercury. Any effect of the mercury on the half-periods of pendulums VI B and VI C is clearly of the same order as changes which occurred in those of the other pendulums, as Table 5 shows. Nevertheless pendulums VI B and VI C are known to have suffered a physical change and it is therefore considered better to exclude them. All six pendulums were used in deriving the mean differences between South African stations, as the mercury accident had occurred before the first South African observations.

Table 5

Gravity differences

Unit cm/s²

Pendulum	T–M	T–J	T–P	M–J	P–J
I A	1·5494	2·6476	2·5673	1·0982	0·0803
I B	1·5494	2·6468	2·5669	1·0974	0·0799
I C	1·5495	2·6471	2·5669	1·0976	0·0802
VI A	1·5498	2·6475	2·5678	1·0977	0·0797
VI B	1·5485	2·6462	2·5663	1·0977	0·0799
VI C	1·5487	2·6466	2·5670	1·0979	0·0796
Mean of six	1·5492	2·6470	2·5670	1·0978	0·0799
Std. error of mean	0·0003	0·0003	0·0002	0·0001	0·0001
Mean of I A, I B, I C, VI A	1·5495	2·6472	2·5672		
Std. error of mean	0·0001	0·0003	0·0003		

T = Teddington, M = Mowbray, J = Johannesburg, P = Pretoria.

Browne & others (1950) point out that effects of sway of the support and of ground motion are less if gravity differences are calculated from the mean of the periods of the two pendulums swung as a pair, than if individual pendulum periods are used. This involves giving double weight to the pendulum in each set which is swung as a member of both pairs (I A and VI B in the present work). Professor Hales and the writer are of the opinion, as at the time of the earlier pendulum measurements, that where all observation sites are stable in character, sway and ground motion are likely to be less important than changes in length of the pendulums, and unknown effects such as that discussed in connexion with the observations at Pretoria. If this is so then, as Cook has remarked (Cook 1957, p. 232), it it best to use individual pendulum periods with unit weight in calculating gravity differences. Gravity differences have therefore been found from the individual pendulum half-periods with unit weight. The alternative decision would, in view of the mercury accident, have made the connexion with Teddington rest upon Set I of pendulums alone.

Table 6 gives values of gravity at the South African stations, taking the value to be 981·1963 cm/s² at Teddington (Cook 1952). Values given by Rose & Woollard

Table 6

Recent pendulum determinations at the South African Gravity Base Stations

Unit cm/s²

Date	Reference	Base	Pendulums	Johannesburg	Mowbray	Pretoria
1948–9	Hales & Gough 1950	Cambridge	Cambridge invar	978·5497	979·6474	978·6293
1955	Rose & Woollard 1956	Washington	Gulf "M" quartz	978·5504	979·6486	
1956	Gough (present work)	Teddington	Cambridge invar	978·5491	979·6468	978·6291

(1956) and by Hales & Gough (1950) are quoted for comparison. The last mentioned have been increased by 3·5 mgal to correct for the change in the assumed value of gravity to 981·2685 cm/s² in Pendulum House, Cambridge (Cook 1953). It will be seen that agreement is satisfactory between the two sets of data from the Cambridge pendulums, and that magnetic perturbations in the earlier work do not appear to have affected the mean differences greatly. Agreement with the Gulf quartz pendulums is less close but this may reflect systematic differences between the two sets of apparatus. It should be noted that Rose and Woollard state, in the preface to the Technical Report quoted, that some of the results cited in this report, particularly pendulum results in South Africa, are of a preliminary nature and are not to be regarded as final values. Rose & Woollard (1956) give results from two connexions between Washington and South African stations using Worden gravimeters. The values given agree reasonably with those quoted in Table 6.

Table 7 gives gravity differences within South Africa found in 1948–9 and in the present work. The difference between Pretoria and Johannesburg from the

Table 7

Gravity differences within South Africa in 1948–9 *and in* 1956.

Unit cm/s²

	M–J	P–J
Hales & Gough 1950	1·0977 ± 0·0003	0·0800 ± 0·0008
Present work	1·0978 ± 0·0001	0·0799 ± 0·0001

J = Johannesburg M = Mowbray P = Pretoria

earlier work is given as 80·0 mgal in Table 7 and as 79·6 mgal by Hales & Gough (1950). The latter value was derived from thirty-six swings made over a period of four months at Johannesburg and eight swings made on 1948 August 5 and 6 at Pretoria. A difference more comparable with the difference found in the present work is that between the 10 swings at Johannesburg between 1948 August 3 and 9 and the 8 swings at Pretoria. This is the difference quoted in Table 7.

4. Acknowledgments

Mention has been made of the writer's indebtedness to Mr B. C. Browne, who first suggested the project, and made the closing observations at Teddington. In addition to others mentioned in the text the writer wishes to express appreciation of help given by the Director and staff of the National Physical Laboratory, Teddington, and in particular Dr A. H. Cook; the Directors and staffs of the Trigonometrical Survey Office, Mowbray, and of the Geological Survey Office, Pretoria; Professor A. L. Hales, Dr E. J. Marais and Dr J. N. van Niekerk. Mr C. B. van Niekerk assisted with all the South African observations. The work was done as an official project of the National Physical Research Laboratory, Council for Scientific and Industrial Research, Pretoria, and the permission of the C.S.I.R. to publish this paper is acknowledged.

National Physical Research Laboratory,
C.S.I.R., Pretoria,
South Africa.
1958 *July* 7.

References

Browne, B. C., Cook, A. H., McCarthy, E. J. & Parasnis, D. S., 1950. *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **6**, 91.

Bullard, E. C., 1933. *Proc. Camb. Phil. Soc.* **29**, 288.

Cook, A. H., 1952. *Proc. Roy. Soc. A* **213**, 408.

Cook, A. H., 1953. *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **6**, 494.

Cook, A. H., 1954. *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **7**, 1.

Cook, A. H., 1957. *Mon. Not. R. Astr. Soc. Geophys. Suppl.* **7**, 228.

Hales, A. L. & Gough, D. I., 1950. "Measurements of Gravity in Southern Africa", Govt. Printer, Pretoria.

Rose, J. C. & Woollard, G. P., 1956. Technical Report of the Woods Hole Oceanographic Institution, No. 56–72.

Magnetic Cleaning of Rocks in Palaeomagnetic Research

J. A. As* and J. D. A. Zijderveld†

(Received 1958 July 16)

Summary

It has been observed that the remanent magnetism of rocks is often the resultant of two magnetizations: firstly a magnetization with low coercive force, mostly directed by the local present Earth's field; and secondly a magnetization with high coercive force which shows the direction of the field from the period of the rock formation.

It is shown that it is possible to remove the disturbing magnetization of low coercive force while saving a good deal of the fossil magnetization with the aid of partial demagnetization. This was carried out by a combination of alternating fields and heating.

Generally a demagnetization with alternating fields up to 300 oersted (effective) at a temperature of 150 °C appeared to be sufficient to clean the rocks.

1. Introduction

In palaeomagnetic investigations it has often been observed that there is a great dispersion in the directions of magnetization of rock-specimens of the same age and the same region even if the specimens come from the same formation. In this case the directions plotted in a stereographic projection often show a belt and are situated between the directions of the ancient field and the Earth's present field in that region. This has been already reported by some investigators and the explanation introduced is that the present field has influenced the magnetism of the rocks (Green 1957 b).

To check whether the magnetization in rocks is a stable fossil magnetization, some stability tests have already been developed (Graham 1955, Irving & Runcorn 1957 and Nagata 1953). However, these stability tests give only a general idea on the reliability of the magnetism of rocks. In practice it is impossible to perform these tests on all rock-specimens of the collection. For this reason an attempt has been made to develop a method of magnetic cleaning which, after application, leaves only the stable fossil remanent magnetism.

2. Principle of magnetic cleaning

Our starting-point was the idea that the magnetization measured in rocks is a combination of different magnetizations, namely a magnetization directed according to the ancient field in the period of deposition, metamorphism or diagenesis of the rocks and magnetizations of later periods. It is known that the magnetic

* Koninklijk Nederlands Meteorologisch Instituut, De Bilt.
† Mineralogisch-Geologisch Instituut, Rijksuniversiteit, Utrecht.

particles in a stone have different coercive forces dependent on their composition, shape and size. The magnetization of the particles with a fairly high coercive force can only be changed by a fairly strong magnetic field. In palaeomagnetism, however, a new factor enters, namely time. It is also possible that the magnetization of the particles with a fairly high coercive force is affected by a fairly weak magnetic field, if this field is active during sufficiently long time. This effect becomes noticeable during the long geological times and has therefore to be taken into account in palaeomagnetic research. Néel (1949) introduced the conception 'relaxation time' for this phenomenon, which designates the same value as the conception coercive force. Of a certain ferro-magnetic mineral we may expect that a particle with a high coercive force has a high relaxation time too, and reversely. After the final formation of the rock up to the moment of collecting, the rock specimen has been in the changing Earth field. The direction of the magnetization of the particles with short relaxation time easily follows this Earth field and these particles cause the disturbing magnetizations in the rocks. But the magnetization of the particles with a relatively long relaxation time in respect of the age of the rock is only little, or not at all, affected by the present Earth field and hence represents the original fossil magnetization. The magnetizations of the particles with the relatively short relaxation time are probably characterized by a low coercive force and are thus unstable with respect to demagnetization, whereas the original fossil magnetization has a high coercive force and cannot easily be removed by demagnetization forces. With these assumptions it must be possible to remove the disturbing magnetizations by partial demagnetization.

3. Method

Demagnetization can be performed by an alternating field or by heating, and of course by a combination of both.

In order to demagnetize a specimen by means of alternating fields the sample is put in a coil through which an alternating current is sent from the 50 c/s mains. This coil is placed in a field-free space produced by a Helmholz coil system. The field-free space is regularly checked by a milli-oerstedmeter. The maximum of the produced alternating field was 300 oersted. For the heating of the specimens we had at our disposal a furnace with adjustable temperatures up to 300 °C. To make the rough specimens suitable for the measurements they were cast in orientated position in plaster of Paris in cubes with edges of 10 cm. This system has many advantages; one in particular is that, when the cubes with specimens are heated, the plaster acts as an insulating cover and in this way it is possible to demagnetize them with alternating fields and to measure a rock sample in a hot state.

The magnetic measurements are executed with the aid of an astatic magnetometer developed by one of the authors. This astatic magnetometer contains an astatic system consisting of two small magnets at 5 cm mutual distance, suspended by a very thin nylon thread. The free period of the system is 20 s, the factor of astatism is one thousandth, and the sensitivity is 10^{-6} e.m.u. for 1 mm deviation of the light spot. In the measuring system chosen the magnetic vector of a specimen is measured in three components perpendicular to each other, hereafter called A, B and C component. A is the vertical 'up' component, B is the south component and C is the east component. In order to demagnetize the specimen in the alternating current coil, its three components A, B and C are placed one after the other parallel to the axis of the coil and so each component is exposed to an

increasing and decreasing alternating field in cold or hot state as desired. Immediately after this procedure the sample is measured. To observe the behaviour of the magnetization of the rocks under the process of demagnetization the specimens were progressively demagnetized. Thus a sample was treated with ever-increasing alternating fields up to 300 oersted, in steps of about 30 oersted, and measured after each treatment. Special attention was paid to the alternating current used in the coil system. During the experiments of demagnetization by powerful alternating fields a disturbing magnetization appeared to be induced in the samples. This disturbance, which may be considerable, turned out to be an effect of asymmetric distortions in the alternating current. Despite the small distortions as caused by higher harmonics (less than 1 per cent) a disturbing field of the order of one oersted is produced, when the demagnetization field is 300 oersted. The odd harmonics cause a symmetric distortion with regard to the 50 cycles current and do not cause any trouble. The even harmonics have to be filtered. This was accomplished by a pass filter for the 50 cycles current combined with a filter to eliminate the 100 cycles.

4. Results of the experiments

The specimens of rocks used for these experiments came from the Estérel, a Permian vulcanic region near the coast of the Mediterranean in the south of France. This region consists of some dolerite flows, two thin (8m and 15m) rhyolitic ignimbrites, one very thick rhyolitic ignimbrite (till 200m) and one rhyolitic flow (about 100m, locally called pyromeride). All these flows and ignimbrites are often separated by more than 100m thick formations of tuffs, conglomerates, arkoses and pelites (Bordet 1951). Of these formations more than 500 oriented specimens were collected. A part of these specimens was used in magnetic cleaning tests. Some results of progressive demagnetization are shown in Figures 1–5. In these examples no corrections for geological strike and dip have been made.

According to the assumption made about magnetic cleaning, it may be expected that during the first part of the progressive demagnetization the magnetization with low coercive force diminishes and even vanishes without greatly affecting the original fossil magnetization with high coercive force. The consequence is that the resulting magnetization changes not only in intensity but also in direction. This rotation of the resulting magnetization continues until all the disturbing magnetizations are destroyed and only the very stable part remains; it is supposed that this is the fossil magnetization. If, after that, more powerful demagnetizing fields are applied, only this last-mentioned direction diminishes, which means that the direction of the measured magnetization no longer rotates. When the direction of magnetization stops moving, even with increasing demagnetizing fields, we may assume that the specimen has been cleaned magnetically. This assumption is wholly confirmed by the experiments. In some cases the applied field was not strong enough to show clearly the last stage of the process of cleaning. However, the results obtained up to now may be considered of importance for palaeomagnetic research.

The most essential features may be seen in Figure 1. This is an example of a progressive demagnetization of a dolerite specimen in cold state. The graph shows the changes of the three components A, B and C and the total intensity as a function of the value of the alternating demagnetization field. The stereographic projection shows the calculated directions of the magnetizations. In this and all

a b

FIG. 1.—Progressive demagnetization of a dolerite specimen by alternating fields at room temperature

a—The changes of the three components A, B and C of the remanent magnetization and the change of the total intensity. The unit of the vertical scale is $3 \cdot 0 \times 10^{-5}$ e.m.u. The broken line represents the total intensity.

b.—The projection of the directions of the magnetization during the process of magnetic cleaning

○ = lower hemisphere + = upper hemisphere ○< = direction after a treatment by 150 oersted

△ = direction of the eliminated magnetization ✱ = direction of the present dipole—earth field in the Estérel.

NM = magnetic north The points a–k on Figures 1 a and 1 b correspond.

the other specimens treated by progressive demagnetization, the magnetization vector describes a path in the plane defined by the present local Earth field vector and the direction of the local permian field. It is remarkable that the B component first increases and then decreases with a maximum at about 150 oersted. The change at 150 oersted can also be found in the behaviour of the other components. This phenomenon clearly points to two magnetizations: one in the Permian direction and one in the direction of the present field. It is easy to determine the direction of the magnetization that decreases first. The triangle in the stereographic projection indicates this direction, agreeing approximately with the direction of the present Earth field in the Estérel, which is indicated by an asterisk. The bend in the graph of the B- and the other components at 150 oersted is a consequence of the fact that at this point the original Permian magnetization begins to decrease. At this point the disturbing magnetization is not quite removed, for next the direction composed of the three components is still moving. Even after the sample had been treated in a field of 295 oersted it was not completely cleaned.

The next example is also a dolerite specimen. This sample received the same treatment, now at a temperature of 100 °C. It seems that with a treatment of 295 oersted at a temperature of 100 °C the magnetic cleaning is finished. This was confirmed by treating the specimen with 295 oersted at 150 °C, when only shrinking of the magnetization vector was observed. Also in this example an agreement was found between the direction of the first removed magnetization and the direction of the present Earth field.

Figure 3 shows the progressive demagnetization of a rhyolitic ignimbrite at 100° C and there it is obvious that the specimen is completely cleaned by a field of 295 oersted at 100 °C.

The behaviour of a pelite treated at room temperature is shown in Figure 4. Sediments react in the same way as volcanic rocks. The rotation of the direction of the magnetization is quite clear. The graph shows that above 150 oersted the Permian magnetization is affected but that it decreases slower than does the present field magnetization. Again it can be seen that at room temperature a treatment by a 295 oersted alternating field is not always enough to complete a magnetic cleaning.

Finally, Figure 5 presents the magnetic cleaning process of an arkose. In this case, fortuitous at 150 oersted, the sample is wholly cleaned.

The total effect of cleaning a number of samples by a field of 300 oersted at a temperature of 150 °C is shown in Figure 6. In this figure, data of dolerites, rhyolites, pelites and arkoses are collected. At the top left-hand corner the samples shown have neither been corrected for geological dip nor by magnetic cleaning. At the top right-hand corner the samples have only been magnetically cleaned, at the bottom right-hand corner the samples have been corrected both for geological dip and by magnetic cleaning. When a mean is taken from the uncleaned and cleaned samples there is a difference in direction of about 30° which corresponds to a pole displacement of 18°. The individual directions of magnetization of some specimens showed rotations up to more than 60° during the process of cleaning. (From preliminary experiments on the rhombporphyries of the Oslo region it became evident that these deviations may even be greater.*) The magnetic pole calculated from 14 demagnetized samples of the Estérel is situated at Long. 144° E

* Personal communication of Mr R. O. van Everdingen of the Mineralogisch-Geologisch Institute, Rijksuniversiteit, Utrecht, who is preparing a doctoral thesis on the palaeomagnetic analysis of the rhombporphyries of the Oslo region.

a b

FIG. 2.—Progressive demagnetization of a dolerite specimen by alternating fields at 100 °C.

a.—The changes of the three components of the remanent magnetization and the change of the total intensity. The values for 0 oersted are obtained after heating up to 100 °C. The unit of the vertical scale is $3{\cdot}3 \times 10^{-6}$ e.m.u.

b.—The directions of magnetization during cleaning.
(For explanation of symbols see Figure 1.)
The directions show a regularly decreasing dip with increasing alternating field.

a b

FIG. 3.—Progressive demagnetization of a rhyolite specimen by alternating fields at 100 °C.
a.—The changes of the three components and the total intensity of the magnetization vector.
The values for 0 oersted are obtained after heating up to 100 °C. The unit of the vertical scale is $1 \cdot 5 \times 10^{-5}$ e.m.u.
b.—The directions of magnetization during cleaning.
(For explanation of the symbols see Figure 1.)
The magnetization vector describes a path in which the end-point turns from the lower to the upper hemisphere; the last point shows a dip of 44° upwards.

(For explanation of the symbols see Figure 1.)

The magnetization vector describes a path in which the end-point turns from the lower to the upper hemisphere; the last point shows a dip of 4½° upwards.

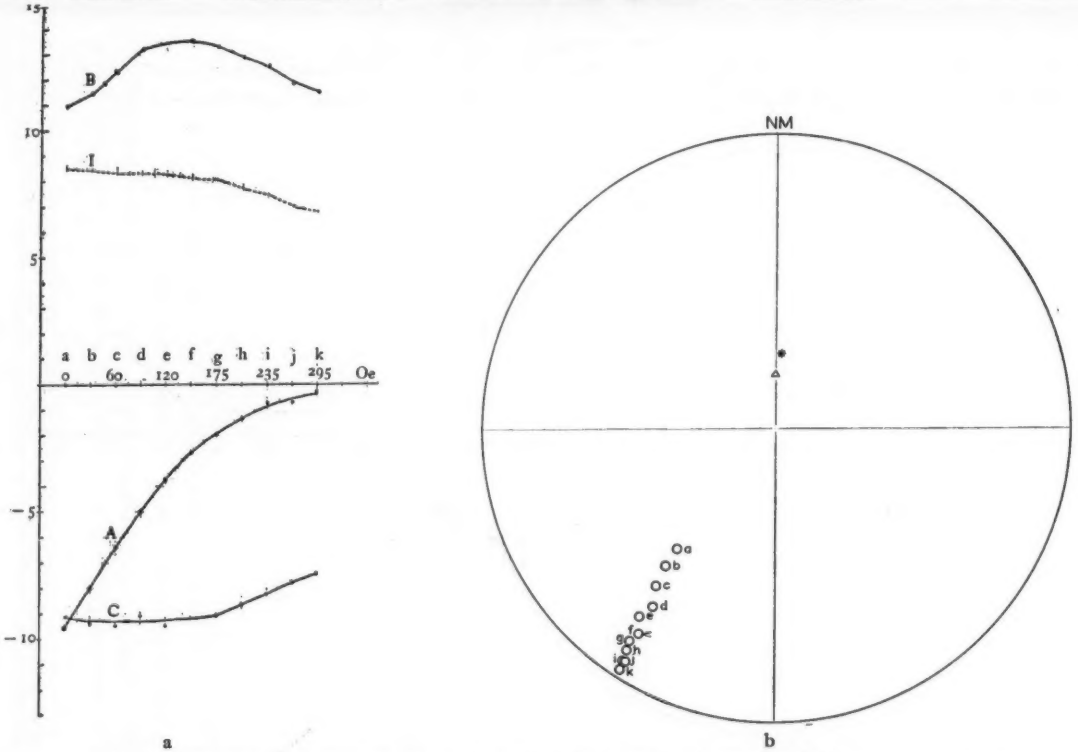


FIG. 4.—Progressive demagnetization of a pelite specimen by alternating fields at room temperature.

a.—The changes of the three components of the remanent magnetization during the magnetic cleaning. The unit of the vertical scale is $3{\cdot}7 \times 10^{-6}$ e.m.u., but for the total intensity it is $7{\cdot}4 \times 10^{-6}$ e.m.u.

b.—The directions of magnetization during cleaning.
(For explanation of the symbols see Figure 1.)

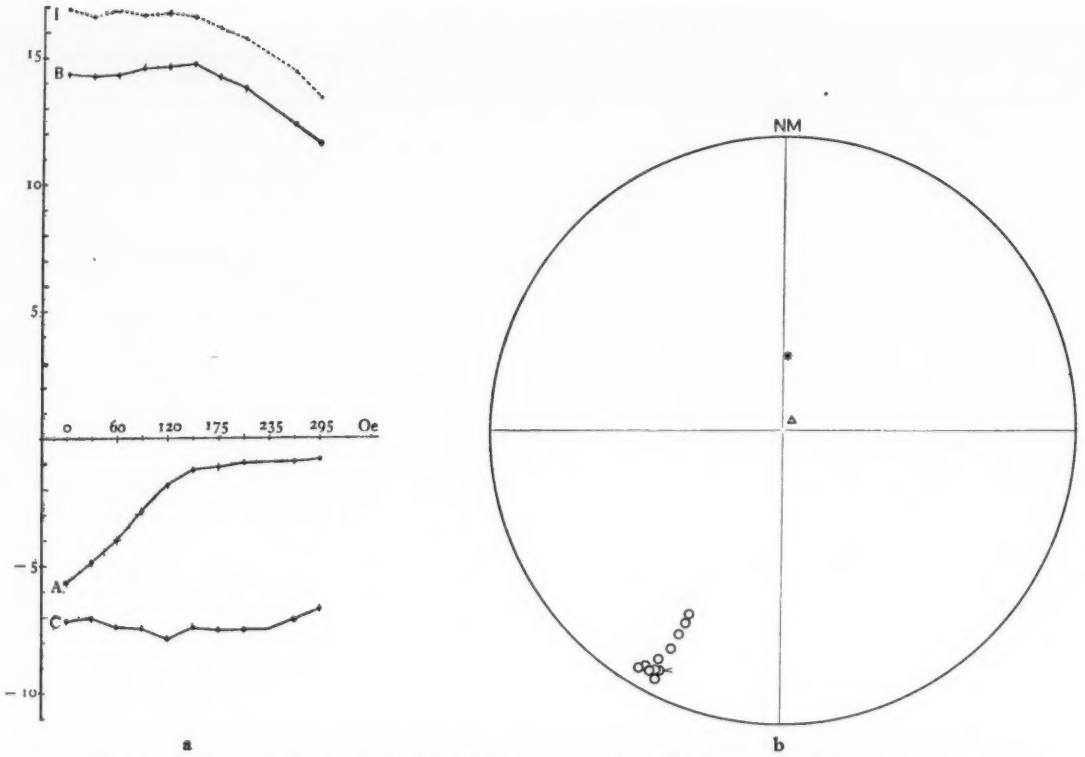


FIG. 5.—Progressive demagnetization of an arkose specimen by alternating fields at room temperature.
a.—The changes of the three components of the remanent magnetization. The unit of the vertical scale is $2{\cdot}7 \times 10^{-6}$ e.m.u.
b.—The directions of magnetization during cleaning.
(For explanation of the symbols see Figure 1.)

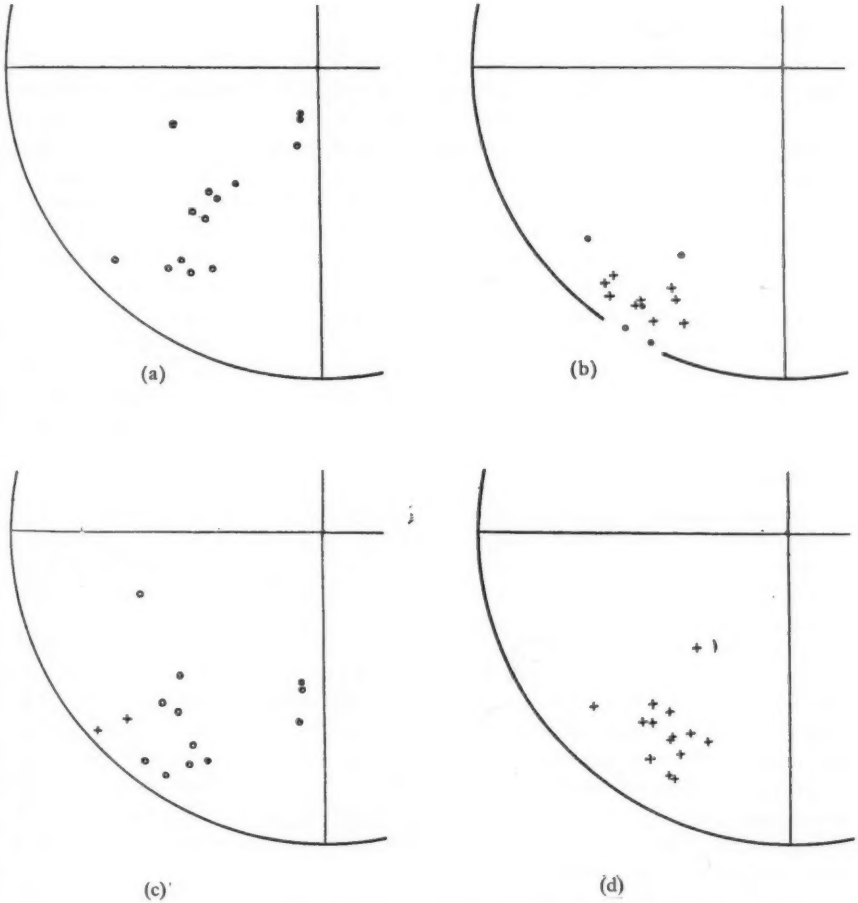


FIG. 6.—The effect of cleaning 14 samples of dolerites, rhyolites, pelites and arkoses, combined with correction for tectonical strike and dip.

+ = upper hemisphere O = lower hemisphere

a.—The measurements before magnetic cleaning and without tectonic corrections.

b.—The directions after cleaning the samples by a field of 300 oersted at a temperature of 150 °C.

c.—The effect of correction for tectonical strike and dip only.

d.—The directions after magnetic cleaning and after correction for strike and dip.

and Lat. 47° N. Of course this position must not be regarded as a definite pole position of the Permian rocks of the Estérel, for the research is still in progress and the bulk of the specimens has not yet been worked on.

5. General remarks

From the well-known formula $\cot\phi = \frac{1}{2}\tan I$ it can easily be seen that a given difference in the inclination of magnetization causes a difference in pole position that is a half of the deflection in the inclination of the magnetization when the pole distance is about 90°, but twice that when the pole distance is about zero. So it is clear that even greater errors than have been found can occur in poles derived from observed magnetic directions in uncleaned rocks. Even when a great concentration of the directions is obtained, it is not certain that a systematic deviation is absent. On account of the great concentration, one gets a small cone of confidence but cones of confidence do not in fact reveal systematic errors.

The dipole axis calculated from a direction of magnetization which results from two dipole fields is also a resultant of the two corresponding dipole axes. This means that the pole position calculated from rocks that are influenced by the present field deviates to or from the North. Therefore the derived longitude of the pole position will be correct but there may be an error in the latitude of the pole.

6. Conclusions

The magnetization of rocks is often the resultant of different magnetizations, namely a fossil magnetization that arose during the formation of the rocks, and a secondary magnetization which often has the direction of the present Earth field. It may be possible that even more than two magnetizations are present but in the Permian rocks of the Estérel this has not been observed.

The disturbing secondary magnetizations are broken down by rather weak alternating fields. Generally an alternating field of 300 oersted combined with heating up to 150 °C is sufficient to remove the disturbing components. The original remanent magnetization is clearly affected at room temperature by alternating fields stronger than 150 oersted. At higher temperatures this point is already reached by weaker alternating fields. However, even after intensive demagnetization, this fossil remanent magnetization was well measurable. It appeared also to be possible to remove the disturbing magnetizations while saving a good deal of the fossil magnetization.

Finally, from these demagnetization experiments it follows that all pole determinations that are based on measurements of remanent magnetizations in rocks from which the disturbing magnetization of the present Earth field has not been removed should be treated with reserve.

7. Acknowledgments

This research has been carried out under the supervision of Professor J. Veldkamp, Director of the Geophysical Division of the Royal Netherlands Meteorological Institute. The authors wish to thank Professor Veldkamp for his valuable suggestions concerning the experiments and the interpretation of the measurements, as well as for his willingness to read and to criticize the manuscript.

The authors are also indebted to Professor M. G. Rutten, Director of the Geological Institute of the University of Utrecht, who stimulated the palaeomagnetic research and proposed to start with palaeomagnetic investigations in the region of the Estérel.

Special mention has to be made of Mr R. O. van Everdingen, who co-operated in the palaeomagnetic research by his investigations of the rhombporphyries, the results of which will be published elsewhere.

Grateful acknowledgment is also due to Mr W. Schuur and Mr G. Klopman for their valuable help in preliminary experiments and to Mr E. Ph. F. H. Blokhuis and the instrument makers of the Royal Netherlands Meteorological Institute for the excellent construction of the instruments.

Koninklijk Nederlands Meteorologisch Instituut,
De Bilt, Netherlands.
1958 *July* 11

References

Bordet, P., 1951. *Etude géologique et pétrographique de l'Estérel. Mémoires pour servir à l'explication de la carte géologique détaillée de la France*, Imprimerie Nationale, Paris.

Clegg, J. A., Almond, M. & Stubbs, P. H. S., 1954. "The remanent magnetism of some sedimentary rocks in Britain", *Phil. Mag.*, **45**, 583–598.

Creer, K. M., 1957 a. "The natural remanent magnetization of certain stable rocks from Great Britain", *Phil. Trans. Roy. Soc. A*, **250**, 111–129.

Creer, K. M., 1957 b. "The remanent magnetization of unstable Keuper Marls", *Phil. Trans. Roy. Soc. A*, **250**, 130–143.

Graham, J. W., 1949. "The stability and significance of magnetism in sedimentary rocks", *J. Geophys. Res.*, **54**, 131–160.

Graham, J. W., 1955. "Evidence of Polar Shift since Triassic time", *J. Geophys. Res.*, **60**, 329–348.

Irving, E. & Runcorn, S. K., 1957. "Analysis of the palaeomagnetism of the Torridonian Sandstone series of N–W Scotland", *Phil. Trans. Roy. Soc. A*, **250**, 83–99.

Nagata, T., 1953. *Rock-magnetism*, Maruzen Co. Ltd., Tokyo.

Néel, L. 1949. *Annal. Géophys.*, **5**, 99–136.

Runcorn, S. K., 1952. *Handbuch der Physik.* Springer Verlag, Berlin, Vol. XLVII, pp. 570–597.

Rutten, M. G., van Everdingen, R. O. & Zijderveld, J. D. A., 1957. "Palaeomagnetism in the Permian of the Oslo Graben (Norway) and of the Estérel (France)", *Geologie en Mijnbouw*, **19**, 193–195.

A Magnetic Survey off the West Coast of the United States between Latitudes 32° and 36° N, Longitudes 121° and 128° W

R. G. Mason

(Received 1958 July 30)

Summary

A total magnetic intensity map covering the area between latitudes 32° and 36° N and longitudes 121° and 128° W is presented. It shows a series of narrow anomalies of about 400 γ amplitude trending north–south for 300 miles over a substantially flat abyssal plain. Some possible interpretations are discussed. The anomalies arise at shallow depths beneath the ocean bottom and are consistent with the presence of relatively thin layers of magnetized material overlying a less magnetic crust; they could equally well arise from topography of the upper surface of a continuous magnetic basement for the most part concealed by an overlying blanket of sediments.

The anomalies are intersected by the Murray fracture zone, which interrupts their pattern in such a way as to suggest a right lateral displacement of about 84 nautical miles.

1. Introduction

Since the latter part of 1952 the Scripps Institution of Oceanography has been towing a total field magnetometer astern one or other of its research ships engaged in routine oceanographic investigations. With a few exceptions, as for example in the study of the Tonga Trench (Raitt, Fisher & Mason 1955), the results have been restricted to long and unrelated profiles obtained during passage of the ship. These have limited application since they give no indication of the lateral extent or direction of anomalous magnetic trends and therefore provide no basis for quantitative geological interpretation.

In August 1955 the opportunity arose to tow the magnetometer behind the U.S. Coast and Geodetic Survey Ship *Pioneer* engaged in making detailed hydrographic surveys with closely spaced and accurately surveyed lines. As a result an extensive area of the deep Pacific off the west coast of the United States (Figure 1) has now been mapped with the detail and accuracy generally associated with airborne magnetometer surveys over the land, and advantage can be taken of the techniques which have been developed for the interpretation of such surveys.

This paper deals with the practical aspects of the survey and discusses some possible interpretations consistent with present day speculation on the nature of the ocean floor. The work was supported by the U.S. Office of Naval Research.

2. The survey

A notable feature of the field operation was the complete coverage of the area with a regular grid of accurately surveyed lines, usually only five miles apart. The position of the ship was determined at approximately eight-mile intervals by means of a radio navigation system using ground wave propagation and fixed beacons on shore. The probable error of an observation varies with time of day and distance from the beacons but is of the order one-tenth of a mile. The ship's tracks were for the most part directed east–west, that is across the principal grain of the anomalous magnetic field, but sufficient lines were run in the north–south direction to eliminate any possibility of ambiguity in contouring.

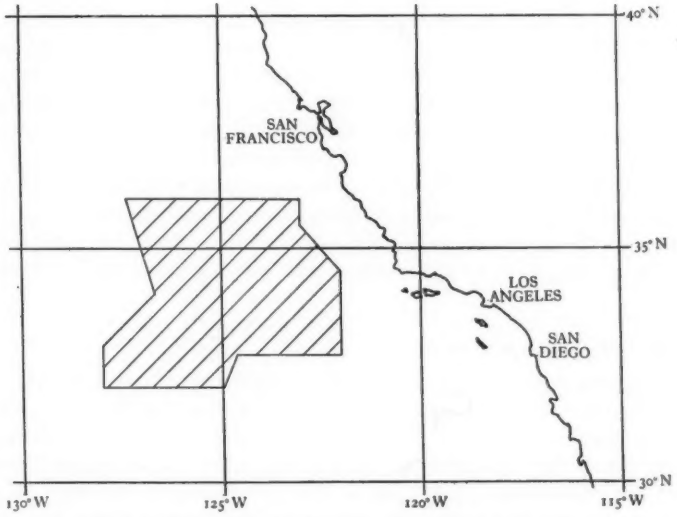


FIG. 1.—Map showing the area covered by the survey.

The magnetometer was an ASQ-3A MAD, originally designed for detection of submarines, modified for geophysical investigations according to plans developed by the U.S. Naval Ordnance Laboratory and further modified to improve its long term stability and render it suitable of use over long periods at sea. It is a gimbal mounted flux gate oriented in the direction of the Earth's magnetic field by two other flux gate elements which control orienting servo motors. The unit comprising the gimballed flux gates and associated motors was housed in a streamlined fish of plastic material which was connected to the electronic and recording equipment on the ship by a 500 ft electrical tow-cable. At that distance the effect of the ship on the measured field was negligible, ranging between about $\pm 5\,\gamma$, depending upon the ship's heading.

The magnetometer was calibrated ashore against a proton precession magnetometer at approximately monthly intervals. Its total drift over the period of the survey was $20\,\gamma$. Taking into account the principal sources of error, namely inherent drift, inaccurate adjustment, and the effect of the ship, the probable absolute error of a single observation is about $10\,\gamma$. With proper adjustment the relative error between any two points on the same line is negligible.

The magnetic map (Figure 2) was constructed by first plotting the measured field value, in 50 γ units, along the ship's track and contouring the result with an interval of 50 γ. The normal geographic change of the total magnetic intensity was determined by dividing the map into 20 mile squares, computing the mean field for each square and smoothing these values in both the north–south and east–west directions by a least squares process. A plot was then made of these smoothed values and this was subtracted from the original plot and the difference contoured with an interval of 50 γ.

No attempt was made to remove the usual time variations of the Earth's magnetic field from the data. However, records of the total field at Palo Alto, near San Francisco, were available for several periods of a few days around the time of the survey and these were found to agree closely with the corresponding records from Tucson, Arizona, magnetic observatory. Since Palo Alto is about 700 miles WNW of Tucson but less than 100 miles to the north of the area under investigation it may be concluded that Tucson records give a fair indication of time variations over the area of the survey. There were no magnetic storms during the course of the survey and the extreme range of the mean hourly values of the total field at Tucson was only 60 γ for the whole period. The mean daily range of the hourly values was 25 γ. These variations are small compared with the amplitudes of the principal anomalies and although they may introduce small errors in the pattern of the contours, particularly in the areas of shallow magnetic relief, they can have little effect on the positions and magnitudes of the more significant anomalies.

3. Preliminary interpretation

The magnetic data and the one relevant seismic section at that time available were sent to the Gravity Meter Exploration Company of Houston, Texas, for preliminary interpretation. On the basis of a number of depth estimates, using techniques which they describe as "such as might be devised putting into effect the principles outlined in GSA Memoir No. 47" (Vacquier & others 1951), they reach the general conclusion that the anomalies arise from relatively shallow structures. Referring in particular to the observed anomaly across the section marked A–A′ in Figure 2, which corresponds approximately to the location of the seismic section of Figure 3, their report states, in paraphrase:

"In an attempt to determine the size and shape of the structures responsible for the anomalies a number of theoretical anomaly curves were computed. From Figure 2 it can be seen that a number of the more pronounced anomalies, particularly in the western part of the survey, are oriented north–south geographic. Figure 4 shows the computed anomaly for an east–west crossing of an infinite north–south block. The thickness of the block is 0·4 times the depth of burial, or approximately 2 km. The susceptibility value used is quite high, 0·0109 c.g.s. The asymmetry of the computed anomaly arises from the difference between the orientation of the block and the orientation of magnetic north. Superimposed on the computed anomaly is the measured anomaly across section A–A′. The agreement is striking. We feel that the anomalies are caused by magnetized material in the form of a relatively thin slab above the normal oceanic crust. This would correspond with the layer marked 'volcanics' on the seismic section.

A point of interest is the high susceptibility value that is necessary for the theoretical curve to fit the observed data. It is high even for the basic igneous

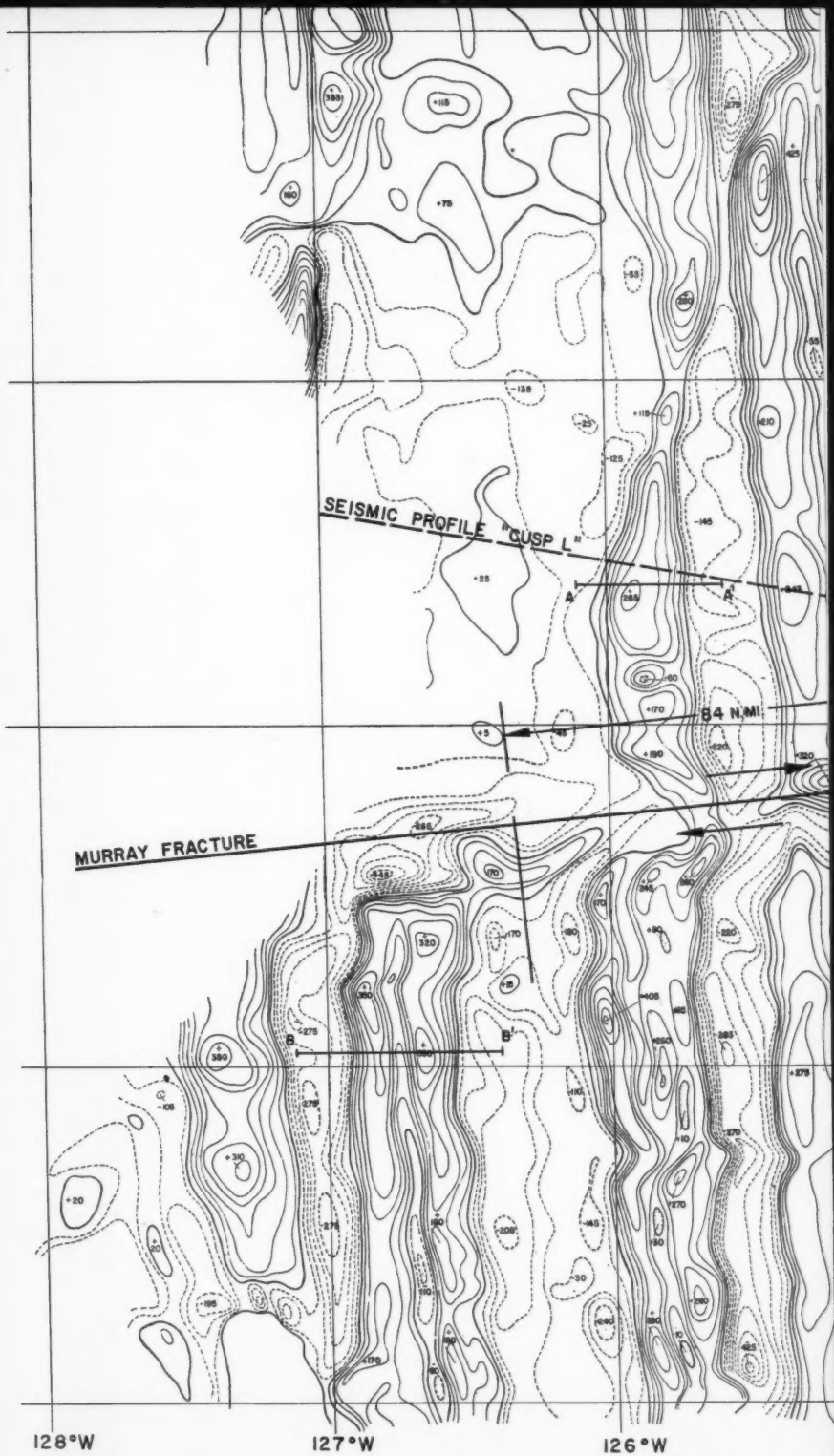
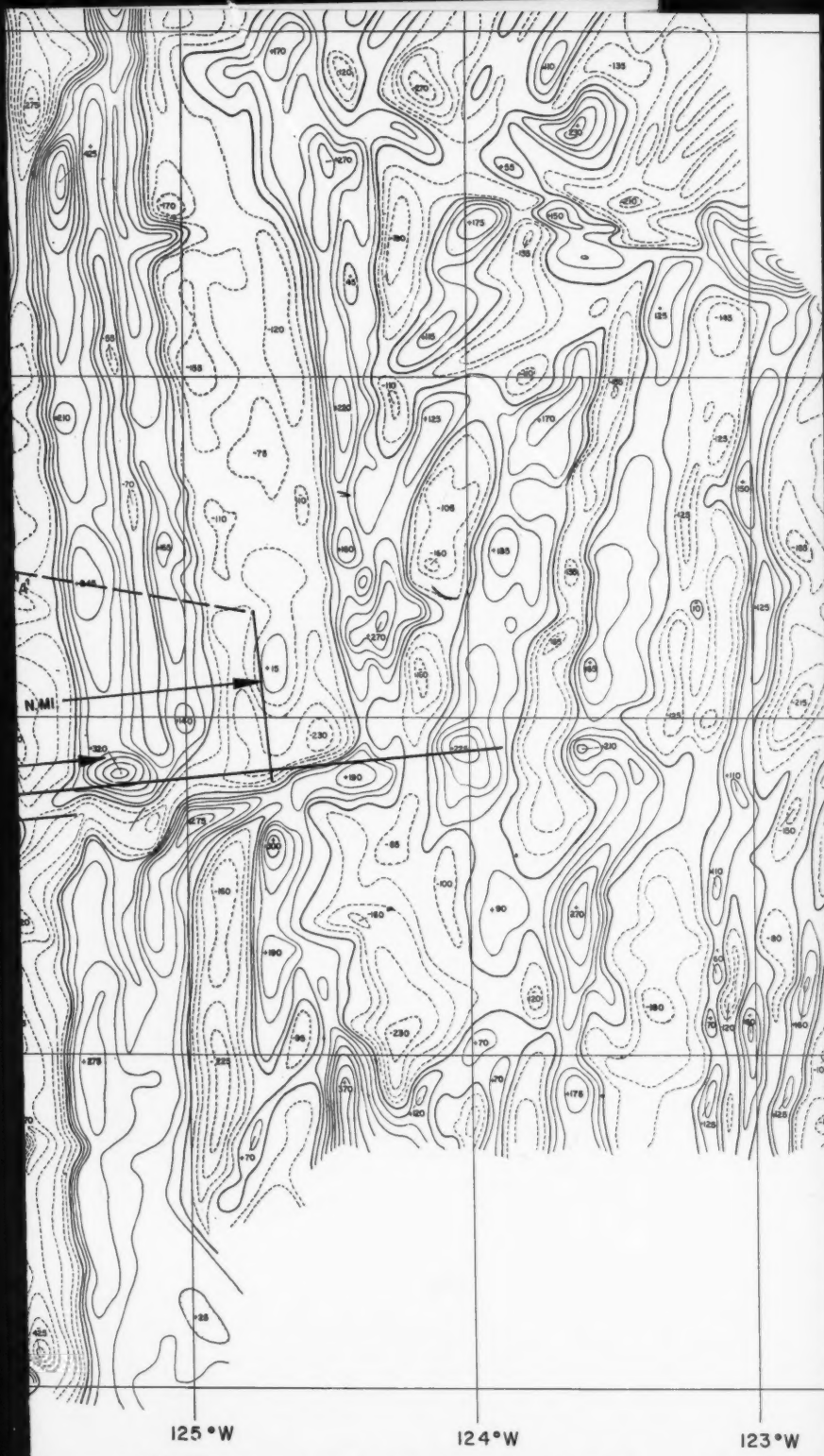
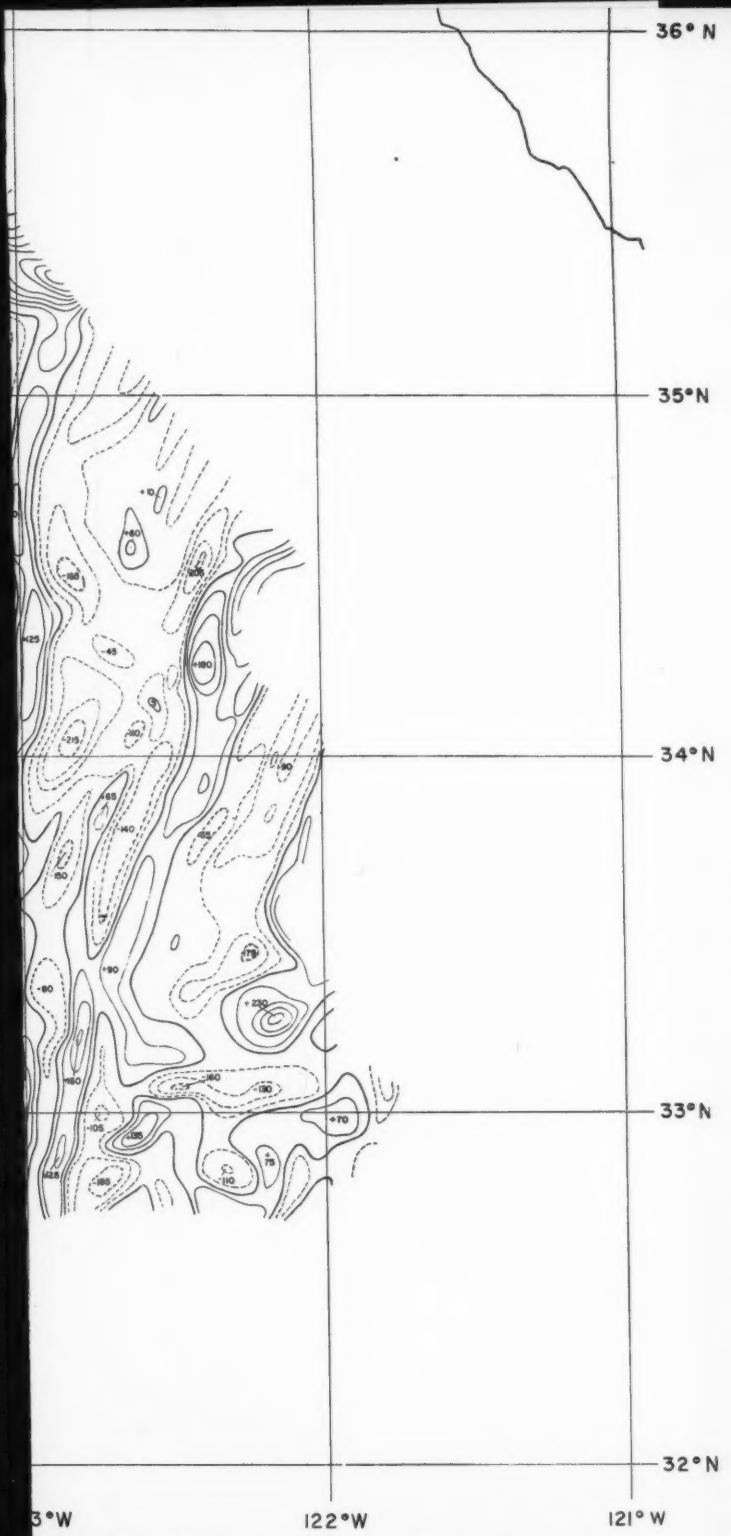


FIG. 2.—Map of the total magnetic intensity after removal of the Earth's normal
indicates the position of the seismic profile inter

Facing page 322]



h's normal field. The contour interval is 50 γ. Lines A–A′ and B–B′ locate the magnetic pro
rofile interpreted in Figure 3. A horizontal displacement of 84 nautical miles along the Mu



netic profiles of Figures 4 and 6 respectively and the dashed line
the Murray fracture is indicated.

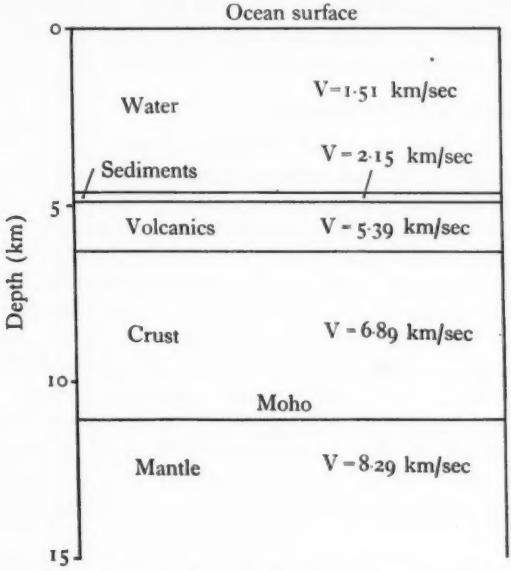


FIG. 3.—Interpretation of seismic refraction profile "Cusp L".

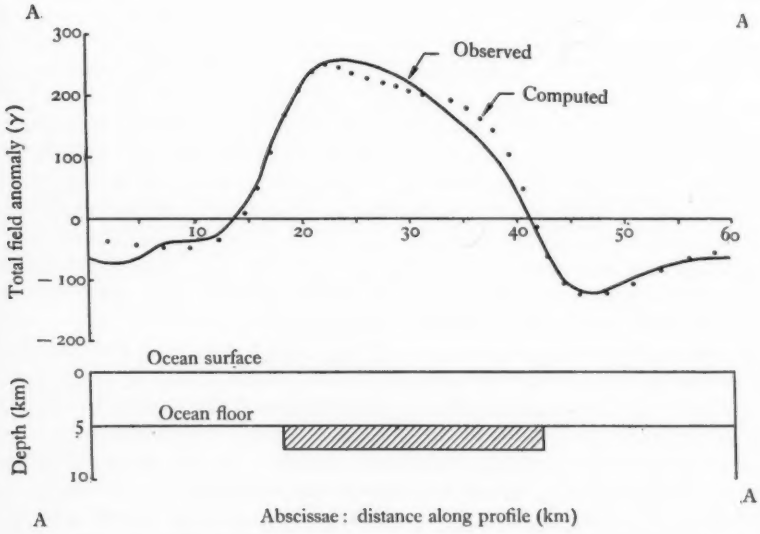


FIG. 4.—Two-dimensional interpretation of magnetic profile A–A′. The dots represent the anomaly which would be produced by an infinite north–south block, of susceptibility 0·0109, computed for a field of 50 000 γ dip 59°, declination 17° E.

materials that might be expected in this area. It is our opinion that such a high value may be indicative of appreciable remanent magnetization of the slabs obtained during cooling in the presence of the Earth's field."

4. Further two-dimensional solutions

The suggestion that the anomalies arise from lava flows is consistent with contemporary speculations on the nature of the ocean floor (Revelle & Raitt 1957). However, it is not necessarily the only possible explanation. The remarkable regularity of the more prominent anomalies throughout the several hundred miles of their length covered by the survey points to a relatively simple cause and encourages a more thorough investigation of possible two-dimensional solutions.

Referring again to magnetic profile A–A′, the solution is restricted in vertical extent by the floor of the ocean at about 4·6 km and, presumably, by the Mohorovičić discontinuity which, according to the seismic data, is here at a depth of about 11 km. It is further restricted in that physical considerations impose a maximum value on the depth of its upper boundary, as will be shown later. If certain simplifying assumptions are made about its shape and state of magnetization, then with a suitable choice of depth and susceptibility it is possible to derive a unique section, within the above limits of depth, which will fit the anomaly exactly.

Figure 5a shows one such section, derived on the basis of a uniformly magnetized single continuous section with a plane lower surface at a depth of 6·3 km, corresponding to the base of the "volcanics", and with induced and permanent magnetization in the direction of the present field equivalent to a susceptibility of 0·015. The derived upper surface, which is unique, extends at its highest point into the sedimentary layer. This and the sections discussed later were built up, by trial and error, of several hundred infinite rectangular strips each 0·5 km wide by 0·2 km thick. The observed curve was matched to within one or two γ.

Similar computations have been made for a plane upper surface. Figure 5b shows three such sections based respectively on equivalent susceptibilities of 0·015, 0·0075 and 0·005, the upper surface in each case lying at a depth of 5 km, corresponding to the base of the sediments. The first is contained almost entirely within the "volcanics" layer, the second extends well down into the crust and has steeper edges, the third is terminated by the Mohorovičić discontinuity. In general, for a fixed upper surface an increase in susceptibility leads to a thinner section of similar shape but more drawn out at the edges, a reduction makes the section thicker and its sides steeper. In theory there is no upper limit to the susceptibility, and corresponding thinness, of the section, but the depth limitation imposed by the Mohorovičić discontinuity leads to a lower limit of 0·005.

The result of increasing the depth of the upper surface is illustrated in Figure 5c. The sides become increasingly steeper until at a depth of 6·2 km, for a susceptibility of 0·015, the structure becomes an almost rectangular block with its lower surface at 7·8 km. This block is the deepest structure of susceptibility 0·015 that can be fitted to the anomaly, though it is possible to make the upper surface still deeper, and the lower surface correspondingly shallower, by increasing the susceptibility. The limiting case is an infinitely thin sheet, of infinite susceptibility, at a depth of 7·0 km.

In their report, the Gravity Meter Exploration Company draw attention to the fact that several of the north–south anomalies appear to have two maxima, with an intervening minimum, and suggest that the lines of minimum field have

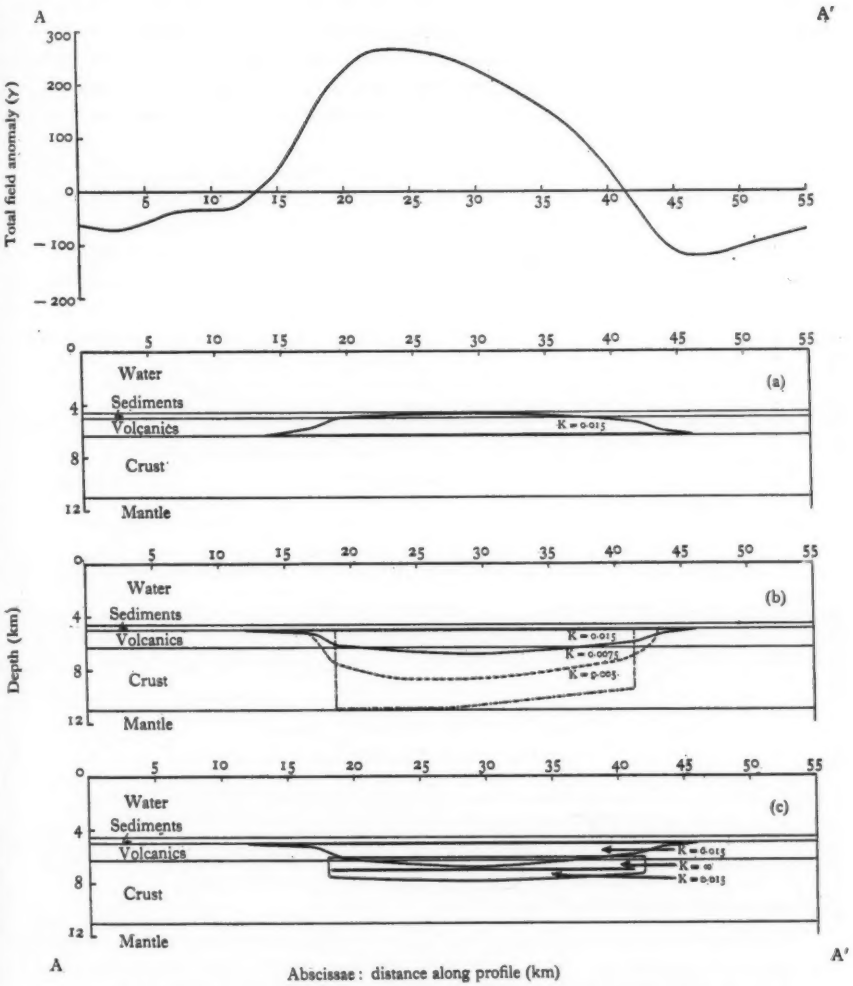


FIG. 5.—Two-dimensional interpretation of magnetic profile A–A′ for a field of 50 000 γ dip 59°, declination 17° E: (*a*) with plane lower surface at 6·3 km depth, (*b*) with plane upper surface at 5 km depth, for various susceptibilities, (*c*) showing the effect of varying the depth of the upper surface.

some structural significance. Figure 6 shows the magnetic profile along the line marked B–B′ in Figure 2, which crosses one such anomaly, together with a derived section based on the assumptions of a plane upper surface at a depth of 5 km and uniform magnetization equivalent to a susceptibility of 0·015 in the present direction of the Earth's magnetic field. In general this section responds to changes in depth and susceptibility in the same way as the sections of Figure 5, except that for greater depths the section breaks into two isolated parts. On the assumption of a depth of 11 km to the Mohorovičić discontinuity, the least possible susceptibility is 0·01.

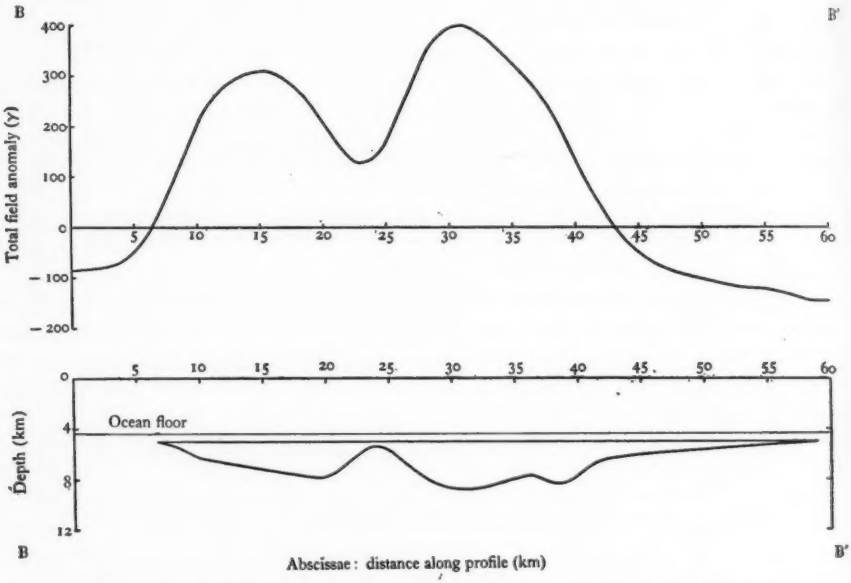


FIG. 6.—Two-dimensional interpretation of magnetic profile B–B′ for a field of 50 000 γ, dip 59°, declination 17° E, susceptibility 0·015.

5. Remanent magnetization

Attention was drawn earlier to the high susceptibility values needed to explain the observed anomalies. The preceding analysis shows that for section A–A′ the least possible susceptibility is 0·005, corresponding to the improbable case of a structure extending from the ocean bottom to the base of the crust. For the more plausible structures the susceptibility must be well in excess of 0·01, or higher than the known susceptibilities of any of the common rocks. This strongly suggests that the rocks involved here are basic igneous rocks, which are characterized not only by a high susceptibility but also by a high intensity of remanent magnetization, commonly several times greater than the intensity of induced magnetization in the Earth's field. Thus in the present case, where the Earth's field is 50 000 γ, an apparent susceptibility of 0·015 could be accounted for by a true susceptibility of 0·005 together with an intensity of remanent magnetization of 0·005 G in the direction of the Earth's field, both acceptable values for a basic igneous rock.

The interesting question arises as to whether, since the direction of remanent magnetization will correspond to the direction of the Earth's field at the time when the rocks were formed, in all probability different from the present direction, anything can be learned about the direction of magnetization that may throw light on the age of the formations. Two factors bear on the problem. Geological evidence (Menard 1955) points to a Cretaceous or early Tertiary age for the Murray fracture, and the magnetic structures are older than this since their pattern is interrupted by it. Palaeomagnetic measurements (see Runcorn 1956 for a summary of relevant information) suggest that since Jurassic times the direction of the Earth's magnetic field in North America has centred around that of a dipole field, with normal or reversed polarity, but that during earlier periods it was quite different.

Figure 7 shows four sections computed to test the effect of varying the horizontal direction of remanent magnetization. The susceptibility was taken to be 0·005

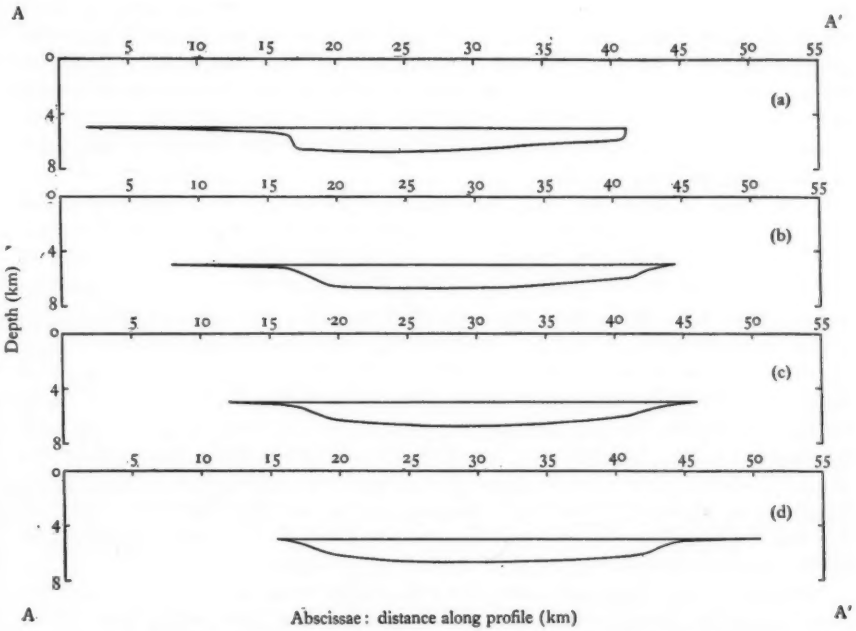


FIG. 7.—Two-dimensional interpretation of magnetic profile B–B′ for a field of 50 000 γ, dip 59°, declination 17° E, susceptibility 0·005 and intensity of remanent magnetization 0·005 G dipping at 59° in azimuths (*a*) 34° W, (*b*) 0°, (*c*) 17° E, (*d*) 34° E.

in all cases and the intensity of remanent magnetization 0·005 G dipping at an angle of 59°, the present dip, but in four different azimuths, namely 34° W, 0°, 17° E (the present magnetic declination) and 34° E respectively. Although the section corresponding to the present direction is perhaps the most symmetrical, there is no compelling reason for preferring one to the other or for rejecting any one. This lack of sensitivity to azimuth is a consequence of the fact that only the components of magnetization perpendicular to the strike, i.e. the vertical and the

east–west, contribute to the anomaly, and for steep dips the former predominates. For a dip of 70° all computed sections would lie between the limiting sections of Figure 6, irrespective of azimuth. A more thorough investigation is beyond the scope of this paper. However, it seems clear that, since any remanent magnetization is required to augment rather than to oppose the present field, the vertical component must be substantially downwards and this makes any appreciable degree of reversed magnetization unlikely if the magnetic poles were anywhere near their present positions.

6. Conclusions

Although the discussion of the preceding sections was based upon a much simplified picture of the situation, there can be little doubt that the major positive anomalies are underlain by an excess, probably totalling at least 1 km in thickness, of a material highly magnetic by comparison with adjacent formations and almost certainly a basic igneous rock. Its upper surface is relatively shallow and probably lies in the "volcanics" layer of the seismic section, or at most no deeper than in the upper part of the crust. Its extent in depth is uncertain but it may be supposed to terminate at a depth no greater than the Mohorovičić discontinuity. Despite its thickness it shows little or no correlation with topography, as far as can be judged from the best available topographic maps, suggesting that it is either buried in consolidated sediments of relatively high seismic velocity or emplaced in less magnetic igneous rocks.

The most obvious and acceptable geological explanation is that the excess material represents lava flows which have spread out over the floor of the ocean, possibly filling pre-existing troughs, or depressions produced by the weight of the accumulating flows. This picture is consistent with the section of Figure 4a and the upper section of Figure 4b, which thin out at the edges in a manner characteristic of lava flows. Within the limits of the survey the major anomalies cover an area of about 50 000 sq km. In extent therefore, and in thickness, the flows would rank with the largest continental lava fields, such as the Columbia River basalts which cover an area of 120 000 sq km and in places reach thicknesses approaching 2 km. An alternative hypothesis, consistent with the section of Figure 4a, is that the excess material represents topography of the upper surface of the crust, itself supposedly the more magnetic layer, brought about by marginal faulting or by folding. In that case it must be presumed that the topography has for the most part been covered by a blanket of sediments.

Whatever their origin and form, the rock bodies which give rise to the north–south anomalies indicate lines of weakness in the ocean floor which were active prior to the formation of the Murray fracture zone. An offset of the pattern of the magnetic features as they cross it suggest a right lateral displacement of 84 nautical miles along the Murray fracture. This displacement, the north–south lineation of the anomalies and the right lateral displacement along the San Andreas fault, may well be related by a single structural hypothesis, possibly connected with a westerly movement of the North American continent relative to the floor of the Pacific.

This paper has been mainly concerned with the north–south anomalies because they are the most striking feature of the magnetic map and because the seismic section provides a framework for discussion which is lacking in the case of the NNE–SSW trending anomalies on the eastern portion of the map. It is hoped that further geophysical investigations, particularly seismic, planned on the basis

of this map will help to throw more light on the complicated structural situation in this area and hence on the more general problem of the relationship between continent and ocean.

7. Acknowledgments

The work was performed while the author was a member of the staff of the Scripps Institution of Oceanography, on leave of absence from Imperial College, London. He gratefully acknowledges the co-operation of the U.S. Coast and Geodetic Survey in connection with the ship's operation and in providing records from Tucson Magnetic Observatory, the facilities for calibrating the magnetometer, and the Palo Alto records, generously made available by the Varian Associates of Palo Alto, California, and the interest taken in the results by Drs L. L. Nettleton and N. C. Steenland of the Gravity Meter Exploration Company of Houston, Texas. He is indebted to various of his colleagues at Scripps for their advice and encouragement, in particular to the Director, Dr Roger Revelle, to Drs H. W. Menard and Victor Vacquier for their advice on the geological and magnetic aspects of the work respectively, to Dr R. W. Raitt who supplied the seismic data and to Mr Arthur D. Raff, who was responsible for the engineering aspects of the project and supervised the field operation.

Imperial College of Science,
*London, S.W.*7.
1958 *July* 29.

References

Menard, H. W., 1955. *Bull. Geol. Soc. Amer.*, **66,** 1149–1198.

Raitt, R. W., Fisher, R. L. & Mason, R. G., 1955. *Geol. Soc. Amer. Spec. Paper* 62, 237–254.

Revelle, R. R. & Raitt, R. W., 1957. "Sediment Thickness of the Pacific Ocean Floor". Paper read at the 10th Annual Conference, Institute of Geophysics, U.C.L.A., Dec. 1957.

Runcorn, S. K., 1956. *Encycl. of Physics*, **47,** Geophys. I, 470–497.

Vacquier, V., Steenland, N. C., Henderson, R. G. & Zietz, I., 1951. *Geol. Soc. Amer. Mem.* 47.

An Investigation into the Calibration of Gravity meters*

R. L. G. Gilbert

(Received 1958 August 11)

Summary

Gravity observations made with gravity meters over large gravity ranges have shown the instruments to be less satisfactory than is desirable. Figures are given showing the errors which have been found using three gravity meters under various field procedures and some possible causes of error are discussed. The scale constants of the gravity meters are shown to change substantially with time, and a system is described which was built into one gravity meter in order to check the scale constant at any time. The results obtained from this device are tabulated and discussed; no satisfactory mechanism has been produced to explain the change in scale-constant, and the calibration device has some use, although not so much as had been hoped.

It is concluded that for the accurate measurement of large gravity differences careful operation of the gravity meters is essential, the calibration of the instrument being checked regularly; and that pendulum measurements may be preferable for the measurement of very large gravity differences.

1. Introduction

The Dominion Observatory makes regular long-range gravity meter observations. Wherever possible, connections are made to any available pendulum bases, in order to improve the accuracy of the National Gravity base network. The connections to pendulum bases also afford a means of calibrating the instruments, the accuracy of calibration depending on the reliability of the pendulum values and the gravity difference between the bases.

Evidence has been accumulating that the scale constants of the gravity meters change with time (Innes & Thompson 1953). Accordingly two convenient pendulum sites, at Ottawa and Washington, were chosen to terminate a calibration line, over which the gravity meters could be checked regularly (Innes 1958). More detailed information on the behaviour of the gravity meters which has been collected over the past three years, using this calibration line, has prompted the construction of a device for quickly checking the calibration of one of the North American instruments. The purpose of this paper is to describe both the behaviour of the instruments and the calibration device.

* Published with the permission of the Deputy Minister, Department of Mines and Technical Surveys, Ottawa, Canada.

2. Methods of gravity measurement

The Dominion Observatory makes an invariable practice of following a looping procedure to eliminate drift when calibrating gravity meters and when establishing primary control points. Drift curves are then plotted so that errors due to drift are minimized. Aircraft are used for long-distance surveys and cars for shorter distances. The distance between stations is arranged so that a reading is taken every hour or less. The length of a "leg" is greater when an aircraft is used, but it is found that the accuracy of the reading for one "leg" is less than when a car is used. However, over a given distance, the increased number of "legs" involved reduces the accuracy of the car work, so that it is comparable to that done by air.

The measurements between Ottawa and Washington have been made using a car exclusively. Three gravity meters have been used—a Geodetic type North American instrument (*No. 137*), a normal North American instrument (*No. 85*), and a Worden gravity meter (*W. 44*). These instruments will generally be identified by number henceforth. The distance between the two bases is about 700 miles, and twenty-four intermediate stations are used. The route has changed slightly since the programme was started, as have some of the stations. However, the changes have been made so that never more than two consecutive stations were altered, and in all cases the old and new stations have been connected by looping.

3. Results of base-line looping

A tabulation of all the readings made during the many runs would be tedious, and the important facts may be presented more simply.

The accuracy of repetition depends to a considerable extent upon the instrument involved. The calibration line stations have been measured so many times that, assuming values of gravity at Ottawa and Washington, the probable error of the adopted gravity difference between adjacent stations is about 0·01 mgal. If the scale constants of the instruments are adjusted to give the best fit, for each traverse, then *W. 44* has an r.m.s. error of 0·04 mgal, *No. 137* one of 0·05 mgal, and *No. 85* has an r.m.s. error of 0·08 mgal for the gravity difference between adjacent stations. It should be noted that the Worden instrument, *W. 44*, is used with the small dial only; this instrument has a Geodetic dial, and if it is used the error is approximately tripled. The scale constants of the instruments are calculated to have accuracies of 1 part in 10 000 or better for a given adopted gravity difference between Ottawa and Washington. The variations of scale constants of the three instruments are plotted against time in Figures 1 to 3, and it is evident that there are real changes in the calibration. It has been suggested that Worden instruments have a constant whose value changes with temperature by approximately 1 part in 1 000 for 17 °C, corresponding to the temperature coefficient of the shear modulus of elasticity for fused silica. Variations of scale constant determined with *W. 44* cannot be explained in such a manner.

It can be seen that the scale constants of all the instruments change when they are repaired, as might be expected. The thermostat relays in the North American instruments occasionally weld themselves in a closed position, and the temperature of the instrument rises exponentially towards about 100 °C. When the instrument has been overheated in this way, the scale constant usually changes, in one case by more than 1 per cent. There have been no facilities for measuring either the duration of the incident or the maximum temperature reached, although it is known that

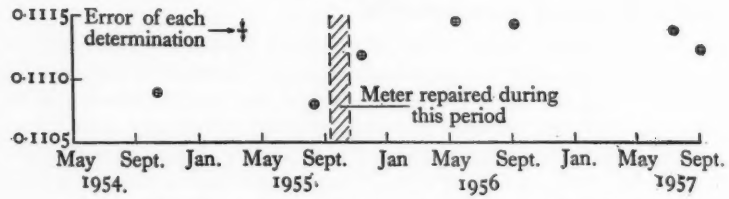


FIG. 1.—Worden No. 44: variation of scale constant with time.
Ordinate: scale constant, mgal per div.

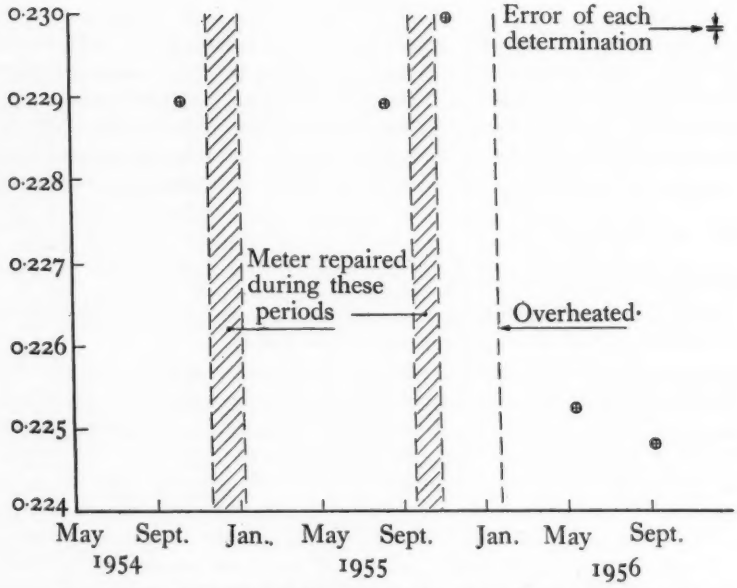


FIG. 2.—North American No. 85: variation of scale constant with time.
Ordinate: scale constant, mgal per div.

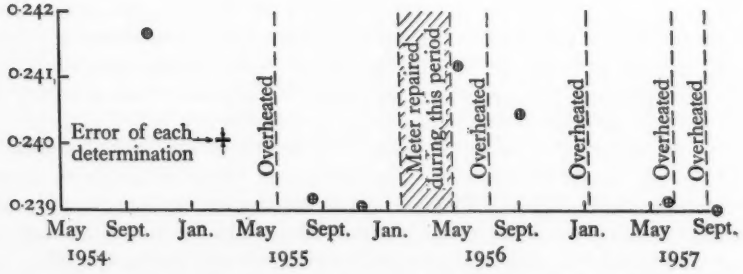


FIG. 3.—North American No. 137: variation of scale constant with time.
Ordinate: scale constant, mgal per div.

the temperature has usually considerably exceeded 50 °C. As well as the above two changes, of which the cause is known and can be guarded against, other changes occur for no known reason. The Worden instrument in particular, which is constructed entirely of fused silica, would be expected to have a fixed calibration, but that this is not so can be seen from Figure 1. Whilst calibrating other gravity meters recently it was found that the scale constants differed depending on whether the calibration was made in a direction of increasing or decreasing gravity. In the case of three Worden instruments, the variation ranged from 1 part in 1 000 to an amount which was less than the error of determination. This effect has yet to be investigated more fully.

4. Causes of instrumental error

The Worden gravity meter, which has no thermostat, shows a very strong correlation between temperature change and drift rate. If *W. 44* is mounted in a thermostat, the drift curves are very much improved. When the drift curves of the two North American instruments are compared, they show many similarities. In order to check that the thermostats were working correctly on the two North American gravity meters, thermometers were mounted on the case to read the temperature of the lid of the inner temperature enclosure to 0·01 deg C. These have shown a variation in the inner temperature of up to 0·05 deg C during the day, but there appears to be but little connection between the temperature and the drift curve. The barometric pressure at the stations does not appear to influence the drift directly, but changes of barometric pressure may affect the temperature of the gravity meter, the effect being integrated over a considerable period. The frame in which the gravity meters are carried in the car is padded and only extends about half-way up the meter, whilst the thermometer mentioned above is mounted close to the thermostat element at the top of the instrument; it is possible that a thermal gradient may be set up in the meter, its value depending on the external temperature. This effect would also be integrated. It is noticeable that on a day where the temperature stays fairly steady, the drift tends to be small. In this connection it may be mentioned that whilst Martin publishes results which point out the desirability of correcting for the internal temperature (Martin 1954, pp. 29–30), his initial readings at a station, which correspond to normal looping readings, are not improved by the corrections. His method of reading the instrument over a period of around two hours is not suitable for normal survey work in Canada, as many gravity stations are far from suitable buildings and the temperature inside a car often changes very rapidly when the car is stopped for some time.

The gravity meters were taken from Ottawa to Washington in May 1956, reading at the intermediate stations without looping. The journey occupied two days and one night; the over-night drift was allowed for, and then a uniform drift rate postulated over the two days. Tidal effects were also computed. The values of gravity at the intermediate stations are known with an accuracy of 0·01 mgal from previous looping, so the error at each station can be found. *No. 137* gave the best results, with a r.m.s. error of 0·13 mgal at the intermediate stations, whilst *No. 85* and *W. 44* gave errors of 0·40 and 0·52 mgal respectively. Compared with the looping procedure carried out later that month, the error for *No. 137* is doubled, that for *No. 85* is quadrupled and that for *W. 44* is multiplied fourteen times. The calibration constants from the run differed from that obtained by looping by 1 part in 1 000 to 1 part in 200. The results from the two North American instruments show how the observations taken without looping emphasize the defect

of a slightly inferior instrument, whilst the particular Worden used is seen to be unsuitable for this type of work.

5. The calibration device

When long-range measurements are made, the changes in calibration of the instruments are of importance. An attempt was made to build a device to check the variation of the scale constant of *No. 137*, by loading the beam of the gravity meter with a weight and measuring the change in reading. A small sapphire ball is used as the weight and is captive in a metal cage. A carrier is mounted on the beam of the gravity meter and has four arms which project vertically. When

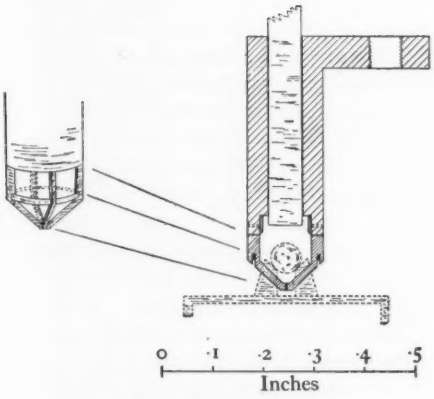


FIG. 4.—Cage assembly.

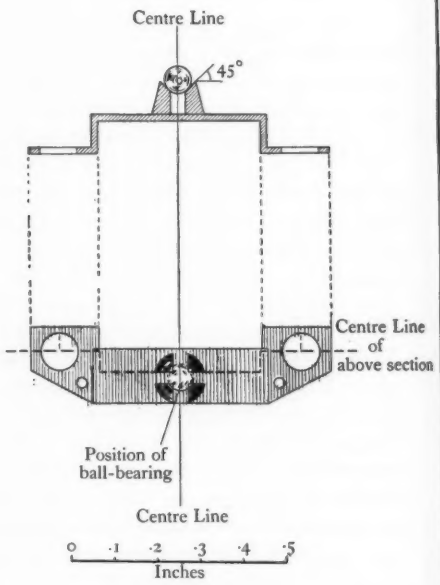


FIG. 5.—Ball carrier.

the cage is lowered, the ball rests on these arms, whilst the cage does not touch either the carrier or the ball. Figure 4 shows the cage, ball and carrier in the position where the ball is resting on the carrier and Figure 5 shows the construction of the carrier, which is mounted on the gravity meter beam. Consecutive readings with the ball loaded on and removed from the beam agree within 0·1 division, which is as well as the instrument can be usefully read. The change in reading is about 350 divisions.

6. The effect of changes of gravity and changes of mass on the North American gravity meter

The working system of the North American gravity meter is shown in Figure 6. The reset control of the gravity meter moves the top end of the reset spring approximately vertically, whilst the reading system moves the fulcrum "O" vertically.

Taking moments about "O" when the value of g is g_0, and the beam is horizontal,

$$Mg_0c \sin\theta = Td + \tau b \sin\phi,$$

M being the total mass of the beam, c the distance from the fulcrum to the centre of gravity, T the tension in the main spring and τ the tension in the reset spring.

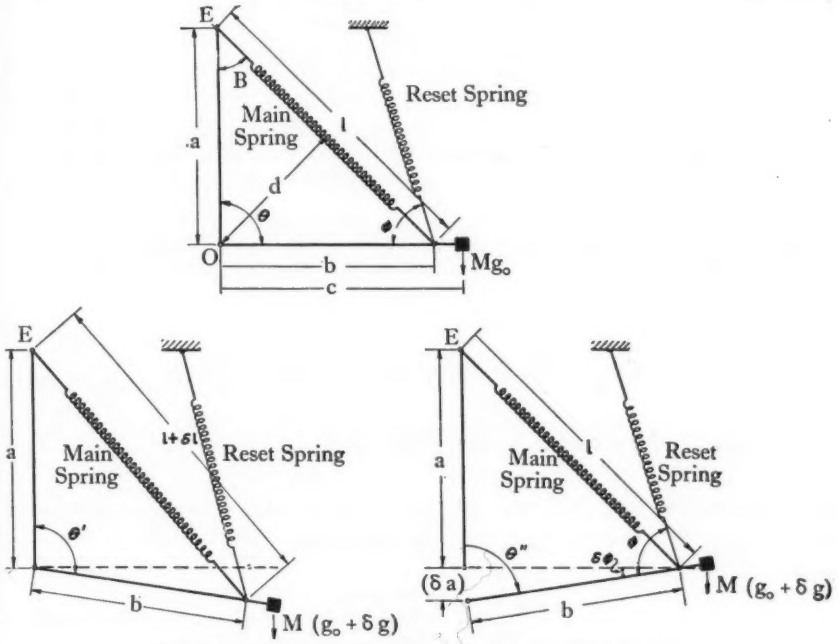


FIG. 6.—Principle of the North American gravity meter.

The main spring has "proportional length" properties—that is

$$T = kl.$$

Now

$$\frac{l}{\sin\theta} = \frac{b}{\sin B}, \text{ and } d = a \sin B;$$

therefore

$$Td = k \frac{b \sin\theta}{\sin B} a \sin B = kab \sin\theta;$$

therefore

$$Mg_0c \sin\theta = kab \sin\theta + \tau b \sin\phi. \qquad (1)$$

If the instrument is not reset, and the main spring length is kept constant, then when the value of g is $g_0 + \delta g$, the fulcrum must be lowered by an amount δa to maintain equilibrium.

The equation then becomes

$$M(g_0+\delta g)c\sin\theta'' = k(a+\delta a)b\sin\theta'' + \tau b\sin\phi''.$$

Now

$$\phi'' = \phi+\delta\phi = \phi+\frac{\delta a}{b};$$

therefore

$$\sin\phi'' = \sin\phi\cos\frac{\delta a}{b}+\cos\phi\sin\frac{\delta a}{b}$$

and

$$Mcg_0+Mc\delta g = kba+kb\delta a+\tau b\left[\frac{\sin\phi\cos(\delta a/b)}{\sin\theta''}+\frac{\cos\phi\sin(\delta a/b)}{\sin\theta''}\right].$$

Now $\theta = 90$, and $\sin\theta'' = 1-\frac{1}{2}\left(\frac{\delta a}{b}\right)^2$ to the second order.

Similarly,

$$\sin\frac{\delta a}{b} = \frac{\delta a}{b},\ \delta a \text{ being small compared with } b.$$

Therefore $$Mcg_0+Mc\delta g = kba+kb\delta a+\tau b\sin\phi+\tau b\cos\phi\frac{\delta a}{b}.$$

Subtracting (1),

$$Mc\delta g = kb\delta a+\tau\cos\phi\,\delta a$$

and

$$\frac{\delta g}{\delta a} = \frac{kb+\tau\cos\phi}{Mc}.$$

It may thus be seen that, unless ϕ is 90°, the scale sensitivity is dependent on τ to some extent. An estimate of the magnitude of this effect can be made.

The value of g, when $\delta a = 0$ and $\tau = 0$ is of the order of 975 gal. When g_0 = 976 gal,

$$\tau b\sin\phi = Mg_0c-kab \text{ (from equation 1).}$$

At $$g = g_1,\ Mg_1c = kab \tag{3}$$

therefore

$$\tau b\sin\phi = Mc(g_0-g_1)$$

and

$$\frac{\tau\cos\phi}{Mc} = \frac{g_0-g_1}{b\tan\phi}. \tag{4}$$

In the North American instrument, the various quantities have values of the order quoted below:

M—100 grammes b—10 cm
c—10 cm ϕ—75°
a—10 cm.

From (3),

$$\frac{kb}{Mc} = \frac{g_1}{a} = \frac{975}{10} = 97{\cdot}5.$$

From (4),

$$\frac{\tau \cos\phi}{Mc} = \frac{g_0 - g_1}{b \tan\phi} = \frac{g_0 - g_1}{10 \times 4} = {\cdot}025(g_0 - g_1).$$

Thus the scale constant will change by an amount of the order of 1 part in 4 000 for a change in g of 1 gal. It should be noted that this is so only when the instrument is reset.

When the ball is lowered on the beam and the instrument readjusted, initial conditions being as given in equation (1),

$$(M + \delta M) g_0 c \sin\theta'' = k(a + \delta a) b \sin\theta'' + \tau b \sin\phi''.$$

Combining this with (1) as before, we get

$$\frac{\delta M}{\delta a} = \frac{kb + \tau \cos\phi}{g_0 c}.$$

Multiplying this by g_0/M

$$\text{gives } \frac{kb + \tau \cos\phi}{Mc},$$

which is equal to $\delta g/\delta a$, the calibration constant. Thus, in order to convert the ball "reading" to scale constant, correction should be made for the value of g where the test is performed.

7. Results of the calibration device

The instrument is more sensitive to levelling when the ball is loaded on the beam—presumably because the centre of gravity of the beam has been raised slightly. This might cause an error of possibly 1 part in 2 000, if the instrument is not correctly levelled. but it should be well below this figure normally. A periodic error in the screw or dial may adversely affect the accuracy—it is thought that the error due to this cause may be about 1 part in 3 000. The periodic error will of course affect all measurements, to an amount of up to 0·03 mgal.

The calibrating device has shown the scale of the instrument to be somewhat non-linear, as is shown in Figure 7. This amount of variation is to be expected from a fairly high-quality micrometer screw. The scatter between the sets of observations made during a single month is probably due mainly to periodic errors in each turn of the screw and dial. Comparisons of the complete runs with the ball are made by plotting curves as in Figure 7 and estimating the change in constant, and also by comparing the mean values of the difference in reading caused by the ball on each occasion. The two methods always agree within 0·1 division.

Table 1 gives the mean values of the several ball tests performed on the instrument, the values of g at the places where the tests were performed, the value of the ball tests divided by g (which should be proportional to the scale constant), occasions on which the instrument overheated, and occasions when the scale constant was determined along the Ottawa–Washington line. Investigations into the

effect of levelling the instrument showed that the ball test gave results 0·15 division different depending on whether the instrument was levelled when reading 5 000 divisions or 0 divisions; accordingly, tests made since June 1957 were performed with the instrument levelled at around 2 500 divisions. The instrument is level when the axis joining the fulcrum "O" and the centre of gravity of the mass is horizontal; as the fulcrum moves with a change in reading, so the "level" position changes slightly.

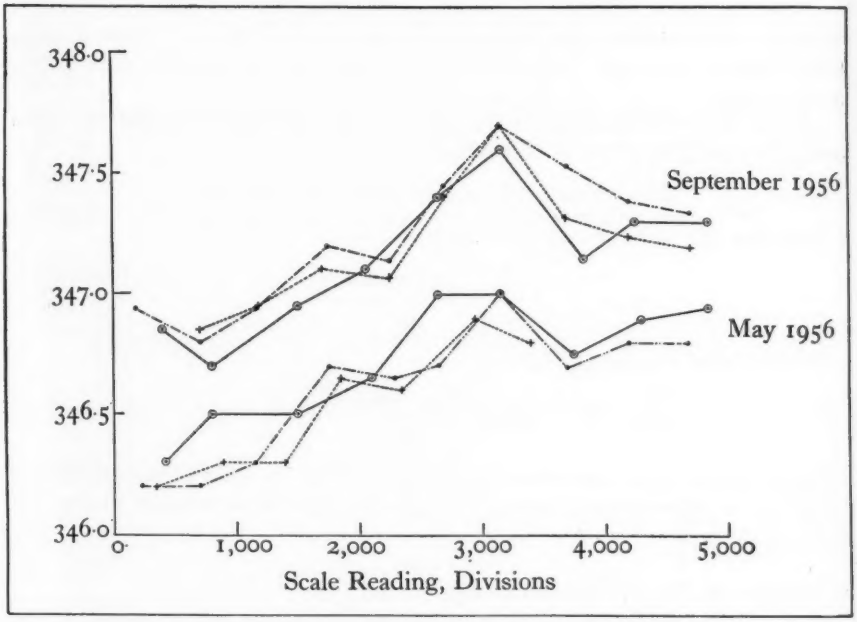


FIG. 7.—Results from Calibration Device.
Ordinate: Effect of Ball, scale division.
+----------+ Washington
⊙————⊙ Ottawa
●—··—··—··—● Syracuse

It is regrettable that, during the past two years, the instrument overheated on an unusually large number of occasions. There is a tendency for the first ball test performed after recent overheating to give a high value in column 5, and for the rest of the values to agree within much better than one part in 1 000. The value obtained at Resolute is exceptional in that the variation with scale-reading was quite different from normal, showing very small variations with scale reading. From the internal consistency of reading, and accuracy of repetition, the accuracy of the test would seem to be of the order of one part in 3 000.

When the values given by the ball test are compared with those from calibration runs, a very different picture may be seen. The change in constant from May 1956 to September 1956 was 0·29 per cent, whilst the ball test showed a change of 0·11 per cent. Between September 1956, and June 1957, the scale constant changed by 0·55 per cent, whilst the ball test indicated a change of 0·90 per cent. From

Table 1

Results of ball test on North American Meter No. 137

Date	Place	Effect of ball	Value of gravity	Effect of ball ÷ g	Comments
1956		div.	gal.		
May	Ottawa	346·73	980·62	0·35358	
May	Syracuse	346·6	980·40	0·35353	
May					Calibration constant 0·24116
July					Overheated for short period
September	Ottawa	347·15	980·62	0·35402	
September	Syracuse	347·24	980·40	0·35418	
September	Washington	347·2	980·12	0·35424	
September					Calibration constant 0·24045
1957					
January					Overheated for considerable time.
February	Binghamton	350·28	980·26	0·35733	
April	Resolute	351·65	982·86	0·35788	
April	Churchill	350·97	981·77	0·35748	
April	Ottawa	350·5	980·62	0·35742	
June					Overheated for short period
June 10	Ottawa	350·7	980·62	0·35763	
June 10	Syracuse	350·35	980·40	0·35735	
June 10					Calibration constant 0·23914
June 23	Manitoulin	350·3	980·65	0·35721	
June 23	Manitoulin				Overheated
June 24	Manitoulin	350·58	980·65	0·35750	
July	Swift Current	350·17	980·88	0·35700	
July	Calgary	350·19	980·83	0·35703	
August	Prince Albert	350·4	981·23	0·35710	
August 28					Overheated
August 29	Saskatoon	350·8	981·14	0·35754	
September	Ottawa	350·17	980·62	0·35709	
September	Syracuse	350·06	980·44	0·35704	
September					Calibration constant 0·23901

June 1957 to September 1957, the constant decreased by 0·05 per cent, whilst the ball test indicated no significant change. The discrepancies here are far greater than expected from experimental errors and may possibly give an indication of the mechanism by which the scale constant changes. The ball test may be useful for checking small changes in scale constant and is certainly useful for checking the time at which the changes occur. For large changes in the constant, the accuracy is so low as to be virtually useless.

No satisfactory mechanism has been produced to explain the changes in scale constant; the fact that the scale constant can change by 1 per cent with a change in the reading of much less than 0·1 per cent indicates that the cause is probably not in

the main spring. The disagreement between the ball test and calibration would seem to indicate that the mathematical analysis given above is too much simplified. To produce an error of 0·4 per cent, the position of the ball would have to be moved along the beam by about 0·020 in, which is unlikely, nor is the mass of the ball likely to change by 0·4 per cent.

8. Conclusions

The calibrating device appears to have some use, although a very limited one. The behaviour of Geodetic instruments leaves much to be desired, especially with regard to temperature changes—which are apt to be greater with air work than with car work. For gravity measurements of the highest accuracy, a looping procedure should be carried out—the errors previously attributed to "tares" may well have a thermal origin. The calibration constant of Geodetic meters needs checking at least once a year, and preferably every three months. Due to the uncertainty in the calibration constant, it would seem likely that good pendulum observations may be preferable to gravity meter observations when gravity changes of the order of 1 gal are being measured; in addition, the behaviour of instruments used to interpolate between such pendulum stations needs to be thoroughly investigated.

Dominion Observatory,
Ottawa,
Ontario, Canada:
1958 *August* 5

References

Martin, J., 1954. Base Gravimétrique Francaise Paris–Toulouse, Extension de Toulouse au Pic du Midi. Expéditions Polaires Francaise Resultats Scientifiques No. NS III, 3, Paris.

Innes, M. J. S. & Thompson, L. G. D., 1953. The Establishment of Primary Gravimeter Bases in Canada, *Pub. Dom. Obs., Ottawa.* **16,** No. 8 (Ottawa).

Innes, M. J. S., 1958. The Establishment of a Calibration Standard for Gravimeters in Eastern Canada and the United States. *Trans. Amer. Geophys. Un.* **39,** 195–207.

Research Note

Determination of the Earth's Gravitational Potential from Observations on Sputnik 2 (1957β)*

A. H. Cook

(Received 1958 September 24)

Summary

R.A.E. observations of the rate of rotation of the orbital plane of Sputnik 2 are combined with Jeffreys's (1943, 1952) equations for the coefficients J and D in the spherical harmonic expansion of the Earth's gravitational field to give revised estimates of J and D. The relative uncertainties of the results emphasize the great value of satellite observations and the need for a revision of the spherical harmonic analysis of surface gravity. Comparison of the value of ϵ^{-1} with that deduced from the constant of precession indicates that the Earth is not in a hydrostatic state.

Merson & King-Hele (1958) have shown that kinetheodolite observations of Sputnik 2 give a rate of rotation of the orbital plane significantly different from that calculated from Jeffreys's (1952) values for the coefficients in the expansion of the Earth's gravitational potential. The precision of this observation exceeds that of Jeffreys's values but the coefficients of the second and fourth harmonics cannot be determined separately with the existing data.

Let the gravitational potential be written as usual in the form

$$V = \frac{fM}{R}\left(\frac{R}{r} - \frac{2}{3}J\frac{R^3}{r^3}P_2(\cos\theta) + \frac{8}{35}D\frac{R^5}{r^5}P_4(\cos\theta)\right).$$

Here f is the Newtonian constant, M the mass of the Earth, R the Earth's equatorial radius 6 378·10 km and (r, θ, ϕ) spherical polar coordinates. All other terms in the expansion are ignored since the only other one which the satellite observations could reveal is that proportional to $P_3(\cos\theta)$ and the evidence indicates that this is very small.

King-Hele (1958) has shown that with such a potential, the orbital plane of a satellite rotates at a speed

$$\dot{\Omega} = \frac{g_e^{1/2}R^3}{\bar{r}^2 a^{3/2}} \cdot \cos\alpha\left[J + \frac{J^2R^2}{\bar{r}^2}\left(\frac{19}{12}\sin^2\alpha - 1\right) - \frac{3}{14}D\frac{R^2}{\bar{r}^2}(7\sin^2\alpha - 4)\right].$$

* Communication from the National Physical Laboratory

Here g_e is the equatorial value of gravity, $\bar{r}$ is the harmonic mean radius and a is the semi-major axis of the satellite orbit, and α is the inclination of the plane of orbit to the equator. According to King-Hele's analysis, the terms depending on J and D in the motion of the satellite are separable from those depending on air resistance. Should an interaction between these terms have been omitted there would be a systematic error in this result but, since substantially the same value of the ratio of the observed value of $\dot{\Omega}$ to that calculated from Jeffreys's values of J and D was obtained at different periods in the life of the orbit, it seems that such an error is unimportant.

Let δJ and δD be differences from Jeffreys's values namely, $J = 1{\cdot}637 \times 10^{-3}$ and $D = 10{\cdot}6 \times 10^{-6}$, and let $\delta\dot{\Omega}$ be the difference between the observed value of $\dot{\Omega}$ and that calculated from Jeffreys's values of J and D.

Writing $j = \delta J/J$ and $d = \delta D/J$, we have

$$j(1+2C_1J) - C_2d = \delta\dot{\Omega}/\Omega$$

where

$$C_1 = \frac{R^2}{\bar{r}^2}\left(\frac{19}{12}\sin^2\alpha - 1\right)$$

and

$$C_2 = \frac{3}{14}\frac{R^2}{\bar{r}^2}(7\sin^2\alpha - 4).$$

jJ and d are small compared with J so that the fact that C_1 and C_2 vary by a few per cent during the life of the satellite will not be too serious and accordingly as a first approximation we may take $\bar{r}$ to be 7 042 km and α to be 65·28° in calculating these coefficients*; hence

$$C_1 = 0{\cdot}2511$$

$$C_2 = 0{\cdot}3119$$

Merson & King-Hele's result is that $\dot{\Omega}$(theoretical)/$\dot{\Omega}$(observed) equalled $1{\cdot}0068 \pm 0{\cdot}0003$ (standard deviation). The uncertainty of the equation for j and d arises largely from the uncertainty in α which is 0·02° in 65°.
Hence

$$1{\cdot}0008\,j - 0{\cdot}312d = (-6{\cdot}8 \pm 0{\cdot}3) \times 10^{-3}. \qquad (1)$$

Jeffreys's adjustment of terrestrial data gives

$$j = (0 \pm 2{\cdot}6) \times 10^{-3}. \qquad (2)$$

A further equation for j and d can be obtained from Jeffreys's (1942) study of the Earth's gravitational field. The value of D given above is that used in the International Gravity Formula; it is not derived from observation but calculated on the hypothesis that the geoid is an exact spheroid (on this assumption the potential when expressed in spheroidal coordinates contains no fourth harmonic) and has

* These are the values about half-way through the life of Sputnik 2 (Cornford 1958).

the value $\frac{1}{2}e(7e-5m)$, where e and m have their usual significance. The coefficient, γ_4, of $P_4(\cos\theta)$ in the expansion of surface gravity is then

$$\frac{4}{35}g_e e(e-5m)$$

or since $e = J+\frac{1}{2}m$,

$$\frac{4}{35}g_e\left(J^2-4mJ-\frac{9}{4}m^2\right).$$

If there is in addition a real fourth harmonic in the potential with coefficient δD, the contribution to γ_4 is $8g_e\delta D/7$.

Thus we find that

$$\frac{\delta\gamma_4}{g_e} = \frac{8}{35}(J-2m)\delta J + \frac{8}{7}\delta D$$

or

$$\frac{1}{J}\cdot\frac{\delta\gamma_4}{g_e} = \frac{8}{35}(J-2m)j + \frac{8}{7}d.$$

Jeffreys's harmonic analysis of free-air gravity gives $\delta\gamma_4/g_e = (-0{\cdot}7\pm6{\cdot}4)\times$ $\times\,10^{-6}$ and hence

$$\frac{1}{J}\frac{\delta\gamma_4}{g_e} = (-0{\cdot}43\pm3{\cdot}9)\times10^{-3}.$$

The uncertainty quoted for γ_4 involves the neglect of the non-diagonal terms in the normal equations for the coefficients of the various harmonics and is therefore a minimum estimate. Jeffreys found that the total variance of the nine fourth harmonic terms might be about 16 mgal^2; on this basis γ_4 could be as much as 8·5 mgal so that a standard deviation of 6·4 mgal seems to cover the possible range of γ_4.

With $m = 3{\cdot}450\times10^{-3}$, the observation equation is

$$1{\cdot}23j\times10^{-3} + \frac{8}{7}d = (-0{\cdot}43\pm3{\cdot}9)\times10^{-3}$$

or with quite sufficient accuracy,

$$d = (-0{\cdot}38\pm3{\cdot}5)\times10^{-3}. \qquad (3)$$

Two least squares solutions of equations (1), (2) and (3) have been made, one with weights inversely proportional to the squares of the uncertainties,* the other with equal weights. The results are given in Table 1.

The unweighted solution gives a residual of $3{\cdot}0\times10^{-3}$ or ten times the standard deviation for equation (1) and residuals comparable with and less than the standard deviation for (2) and (3) respectively. The weighted solution gives a very small residual for (1), one of 2·2 times the standard deviation for (2) and one 0·9 times the standard deviation for (3). In view of the few degrees of freedom on which all uncertainties are based, the weighted solution reconciles the data reasonably

* The weights are 100 for equation (1), 2 for equation (2) and 1 for equation (3).

well. The uncertainties are based on 1 degree of freedom only and so are not very reliable. Nonetheless it is useful to compare the value of e with that derived from the constant of precession and from gravity data. The former method gives $e^{-1} = 297{\cdot}34$ with a standard deviation of 0·28 or 0·55 depending on whether the Earth is assumed to be in a hydrostatic state or not (Jeffreys, 1948). The difference between the precessional value for e^{-1} and the satellite value is 0·90, equal to twice its standard deviation on the hydrostatic hypothesis. There is thus some evidence of a real departure from the hydrostatic state.

Table 1

Solutions of observation equations

	Weighted	Unweighted
j	$(-5{\cdot}74 \pm 2{\cdot}6) \times 10^{-3}$	$-3{\cdot}01 \times 10^{-3}$
d	$(+3{\cdot}1 \pm 38{\cdot}2) \times 10^{-3}$	$+2{\cdot}63 \times 10^{-3}$
δJ	$-9{\cdot}4 \times 10^{-6}$	$-4{\cdot}92 \times 10^{-6}$
δD	$+5{\cdot}1 \times 10^{-6}$	$-4{\cdot}3 \times 10^{-6}$
J	$(1{\cdot}628 \pm 0{\cdot}004) \times 10^{-3}$	$1{\cdot}632 \times 10^{-3}$
e^{-1}	$298{\cdot}24 \pm 0{\cdot}36$	$297{\cdot}88$

The uncertainties are standard deviations.

Gravity data alone give values of e^{-1} which vary according to the treatment of the possible longitude terms but are up to 2·0 less than the satellite value. It is important to emphasize that Jeffreys's analysis of the Earth's gravity field, from which the coefficient γ_4 is obtained, is out of date. It depends on data available in 1940 and since then a great deal more material has accumulated, especially in the Pacific Ocean. In view of the precision attainable with satellite observations, it is very desirable to analyse this material using Jeffreys's statistical procedure and so obtain estimates of J and D with uncertainties more comparable with those of satellite observations. The importance of this is the greater in that observations of the Moon and the calculation of J from the precessional constant and the Earth's internal density distribution cannot be expected to give much greater precision than at present.

This note has been prepared for the Satellite Study Group of the Geodesy Sub-Committee of the National Committee for Geodesy and Geophysics, and is published with the permission of the Director of the National Physical Laboratory.

Standards Division,
National Physical Laboratory,
Teddington.
1958 *September* 22.

References

Cornford, E. C., 1958. A comparison of orbital theory with observations made in the United Kingdom on the Russian satellites. Min. of Supply Rep. presented to the I.A.U., Moscow, 1958 August.

Jeffreys, H., 1943. *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **5**, 55.
Jeffreys, H., 1948. *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **5**, 219.
Jeffreys, H., 1952. *The Earth.* (3rd ed. Cambridge: the University Press).
King-Hele, D. G., 1958. *Proc. Roy. Soc. A*, **247**, 49.
Merson, R. H. & King-Hele, D. G., 1958. *Nature* (*London*) **182**, 640.

Letter to the Editors

The Eccentric Geomagnetic Dipole

W. D. Parkinson and J. Cleary

The Gauss coefficients of a spherical harmonic analysis of the Earth's main magnetic field have been published recently (Finch and Leaton 1957) for the epoch 1955.0. The authors state the positions of the poles of the centred dipole (usually called the geomagnetic poles) but not those of the eccentric dipole. The positions of the latter were required here recently, and are presented in case they may be of interest to others. Phenomena not involving the surface of the Earth, such as the deflection of auroral or cosmic ray particles outside the atmosphere, are controlled by the eccentric rather than the centred dipole.

Formulae for deriving the position of the eccentric dipole from the Gauss coefficients have been given by Bartels (1936). On substituting the 1955.0 values into these formulae, we obtain the following results: the eccentric dipole is displaced by 0·0685 Earth radii (about 436 km) from the centre towards a point at latitude 15°·6 N, longitude 150°·9 E (just east of the Marianas). This is 6°·6, or 730 km north of the geomagnetic equator. The poles of the eccentric dipole (i.e. the points where its axis cuts the surface of the Earth) are at 81°·0 N, 84°·7 W and at 75°·0 S, 120°·4 E (i.e. in Ellesmere Is. and in Wilkes Land). The axis of the eccentric dipole is not vertical at these points, but is inclined at 3°·9 to the vertical in the direction of the corresponding geomagnetic pole, i.e. 126°·3 E of N for the north pole and 150°·9 west of north for the south pole.

The field of the eccentric dipole is, of course, parallel to its axis, and so it also is inclined to the vertical at the poles of the eccentric dipole. The eccentric dipole field is vertical at two points which are further from the geomagnetic poles. The positions of these points are 82°·4 N, 137°·3 W and 67°·9 S, 130°·6 E. The latter is close to the observed dip pole near Terre Adelie, but the former is about 1 200 km from the observed northern dip pole which is near Prince of Wales Is. (Hope 1957).

Bureau of Mineral Resources,
Geology and Geophysics,
Department of National Development,
Melbourne, Australia.

1958 *July* 29.

References

Bartels, J., 1936. *Terr. Mag.*, **41**, 225.

Finch, H. F. and Leaton, B. R., 1957. *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **7**, 314.

Hope, E. R., 1957. *J. Geophys. Res.*, **62**, 19.

Notes on the Progress of Geophysics

Geophysical Studies in Polar Regions

The Antarctic Ice Sheet

G. de Q. Robin

Introduction

The concept of the International Geophysical Year has done more than capture the imagination of scientists. The problems of placing men and materials at the most inaccessible spots on Earth have produced an enthusiastic response from transport engineers and explorers while adequate financial support has enabled them to achieve their objectives. Still more remarkable are the recent voyages of nuclear powered submarines under the Arctic pack ice, which open up new and more rapid techniques for the exploration of this oceanic basin. It is therefore not surprising that 1957–58 has seen the available geophysical data on the polar regions increase by an order of magnitude.

Although the major disciplines of the IGY are those most directly linked with solar radiation in its various forms, certain studies of the structure of the Earth were added as the programme was planned, and this review will be limited to some of the latter investigations. Most of this work is still in progress, but brief summaries have been published which are sufficient to outline the principal results to date (IGY Bulletins 1957–8, Hatherton 1958, IGY Glaciological Rep. 1958, Shoumsky 1958).

The main advances in the study of the geophysics of the Earth's crust in polar regions have come from the application of existing techniques of geophysical exploration. Such techniques have proved particularly suitable for studying the ice masses of the polar regions. Field studies have followed the laboratory and theoretical work of the past decade on the flow of ice, with the result that glaciology is now recognized as a subject for geophysical study which, in addition to its own intrinsic interest, may help provide solutions to broad geological problems on the flow and deformation of rocks.

The basic data on the depth and other properties of the polar ice sheets have been gathered by well equipped scientific traverse parties. Seismic reflection shooting methods have provided the main key to ice depth determinations while gravitational and magnetic measurements are used to fill in details between the main seismic stations.

Seismic shooting methods

The contrast in density and elastic wave velocity between ice and rock is so favourable for seismic reflection shooting that rapid exploratory surveys making widely separated spot measurements have proved successful in most cases. Occasional areas are found where the reflecting properties of the glacier bed are poor, as in North Eastern Greenland, and here one has to rely on gravity measurements to a much greater extent (Hamilton 1956). However, frequent double or

triple reflections from the glacier bed confirm that the ice–rock interface usually forms the good reflector which one would expect on theoretical grounds and also show that attenuation of elastic waves in ice is relatively small at the frequencies of the order of 100c/s normally recorded. Ice thickness measurements made by reflection shooting now vary between 100m and 4 200m and the accuracy of depth measurement is normally within two per cent. The technique is therefore adequate but any simplification of the complicated equipment and lengthy procedures involved would be welcome. Unfortunately the complications increase as one climbs onto the high inland plateau of Antarctica. Whereas one kilogramme of explosive on or near the surface is sufficient to produce adequate reflections at lower altitudes, on the cold inland plateau such explosions produce large and prolonged surface waves which tend to block out weak echoes. (Robin 1958). The exact nature of these surface waves is not yet clear, although they are obviously connected with a very high velocity gradient close to the surface of the cold inland ice. A waveguide effect appears to account for some of their characteristics, but does not explain the sudden increase of surface wave energy found when mean ice temperature falls below approximately −30 °C. The only reliable way to avoid this difficulty is to increase the shot depth to 20 or 30m so that very little energy is captured by the surface "waveguide". This has been done with conspicuous success by the Australian traverse team in the Antarctic, while other traverse teams on the Antarctic plateau with less effective drilling equipment have encountered varying degrees of difficulty.

On the floating ice shelves around the Antarctic continent, the theoretical expectation of a reflection coefficient of energy of *P* waves of around 0·16 has not generally been fulfilled in practice, although this figure has been found to apply on some occasions (Robin 1958). The most reliable technique for this problem has been to employ a combined refraction–reflection technique using the reflection from the sea bed.

Refraction shooting techniques using spreads up to 20km have been used successfully by the Russians for measuring ice thickness and wave velocities in the underlying rock (Shoumsky 1958). However in spite of the extra data obtained this technique is slow and uses too much explosive for most exploratory surveys of Antarctic ice. On the small scale, refraction shooting over spreads up to a few hundred metres have been used extensively to determine the velocity gradient, and hence the related density variations in the top 50 to 100m of the ice sheet where snow is changed gradually into glacier ice. (IGY Glaciological Report 1958).

The absence of any discontinuities in velocity in this upper zone and the purity of the ice–air mixture make such polar ice sheets a useful testing ground, intermediate in size between laboratory and earthquake studies, on which experiments on elastic wave problems under accurately known conditions can be carried out. It is to be hoped that the use of three-component seismographs and absolute measurements of energies under these conditions will provide information which will help to consolidate the bridge between certain theoretical and experimental seismological studies, particularly in the case of amplitude problems.

Seismology

In the field of earthquake seismology, a scattered network of stations on the Antarctic continent has been established. Stations have been operated successfully on the thick inland ice (e.g. South Pole) and on a floating ice shelf (Halley

Bay). No major earthquake activity within the continent has been reported (Hatherton 1958), although smaller shocks have been recorded at Halley Bay (Weddel Sea) and at Scott Base (Ross Sea), the latter including activity associated with the active volcano Mt. Erebus. Many shocks from elsewhere in the southern hemisphere were recorded, particularly from the ridge in the Indian Ocean. An interesting feature of microseismic activity was the very low level to which this fell during the winter months at Scott Base, and to some extent at D'Urville Base further north. The explanation may be found to be an effect of the pack ice which covers greatly increased areas of the surrounding ocean during winter months. Another promising field of investigation from which results are awaited are studies of surface waves since these may give information on the mean thickness of the Antarctic ice sheet and thus form a check on the representative character of the many spot determinations of ice thickness.

Gravitational studies

Apart from a very few basic measurements of gravity which have been checked at points on the Antarctic coast line, the main activity has been to use gravity meters for interpolation between seismic soundings of ice thickness. In spite of the difficulty of measuring elevations by aneroid barometers, the method has proved most successful for providing a rapid method of ice depth measurement, even though its accuracy is less than that of seismic soundings. As a change of 1 mgal in the value of gravity is caused by a change of ice thickness of around 14 m, an elevation error of 20 m will cause an error in ice thickness of about 100 m. Local gravitational anomalies arising from changing densities of rocks may well produce larger errors. Elevation measurements should be sufficient for interpolation of ice thicknesses between seismic soundings, but it is difficult to eliminate the possibility of systematic errors occurring over the vast distances between the periphery and central regions of the Antarctic continent when measuring elevations by barometric pressure. For this reason it is difficult at this stage to interpret the reported negative free air anomalies of the order of one hundred milligals on the Antarctic plateau. Even one major levelling traverse using optical methods, of the type carried out in Greenland by the British North Greenland Expedition (Paterson & Slessor 1956), would be of considerable value in the Antarctic. In north Greenland free air anomalies were generally less than 30 mgal over the central portion of the ice sheet (Hamilton & others 1956) thus showing that isostatic compensation for the weight of the ice sheet had taken place. As the establishment of such isostatic equilibrium is believed to take thousands of years, this indicates that this portion of the Greenland ice sheet has been approximately stable for many centuries. Apart from its considerable scientific significance, similar data for Antarctica would provide a tangible return for those administrators who were persuaded to provide financial support for Antarctic research because of the widespread damage which would be caused by sea level changes resulting from a decrease of Antarctic glaciation.

Magnetic observations

Although several traverse parties have taken regular measurements of magnetic intensity, particularly of the vertical component, no preliminary reports on their value have been seen. It appears likely that apart from general confirmation of gravitational anomalies, they will be both less accurate for ice thickness interpolation and of less general significance than gravitational observations.

General glaciological problems

In order to understand the mass and thermal balance of the Antarctic ice sheet a vast amount of data is being collected by many traverse parties. The net annual surface accumulation of snow has been found to vary from 40 cm of water equivalent in some coastal areas to 8 cm or less on the high inland plateau. Ice streams draining the inland area have been found to move up to 3 m per day, (IGY Glaciological Rep. 1958, Shoumsky 1958), but owing to the difficulties of access satisfactory estimates of the rate of discharge of the largest ice streams have still to be made. Until this is done this method of studying the mass balance will remain ineffective. However other evidence now available, such as the domed shapes of the ice sheet, the scarcity of freshly exposed rock surfaces and the small values of the world wide changes in mean sea level, all point to the existence of an approximate mass balance of the Antarctic ice sheet.

Some headway is also being made in understanding the temperature distribution in the Antarctic ice sheet thanks to deep drilling projects carried out by the U.S.A. and the U.S.S.R. Both boreholes showed decreasing temperatures with depth near the surface, but the Russian results near Mirny showed that this effect was reversed at around 200 m depth so that the basal ice temperature was close to the pressure melting point at a depth of just over 500 m. They have used the method of hydro-analogies to study the temperature distribution in the ice, and have obtained reasonable agreement with observations (Shoumsky 1958). This should provide an improved method of analysis, although the advection of cold ice remains the primary explanation of these negative gradients (Robin 1955).

A continuous trend of climatic change may also affect observed temperature gradients considerably, but in order to eliminate the effect of horizontal advection of cold ice, boreholes to study this problem must be sited at a centre of outflow of ice. So far no boreholes have been shown to satisfy this criterion, hence this form of a direct physical record of climatic change has still to be obtained.

The U.S.A. boring at Byrd base was also notable for a 98 per cent core recovery. Half the core has been returned to the U.S.A. for detailed laboratory studies which should prove very valuable, as it will provide a well dated sediment of the past 700 years for studying problems such as the rate of fall of micrometeorites and other particles.

Physiography

At the beginning of 1956 an effective 400 miles or so of ice thickness profile had been obtained from Antarctica. At the time of writing over six thousand miles of profiles have been obtained and further results are anticipated. It now seems likely that the mean thickness of the Antarctic ice sheet is around 2 000 m. While from a geological point of view it has always been clear that the Antarctic block is of continental proportions, some results have again raised the physiographical question of how much of the rock surface lies above sea level. It is now clear that that boundary of East Antarctica which faces West Antarctica is above sea level for at least 2 000 miles, a figure of continental proportions, but two major problems remain. The first is to prove or disprove the existence of an ice filled trench between East and West Antarctica. The evidence to date tends to confirm the existence of this discontinuity which has been postulated by geologists for many years. The second major problem is to find out whether or not the huge ice mass

on East Antarctica has depressed the rock floor below sea level to form a huge basin-shaped depression. It seems reasonable to hope that the U.S.A. and U.S.S.R. will provide the answers to these problems in the 1958–59 field season.

Crustal geophysics

So far no seismic shooting or seismological results have been reported which indicate the depth of the Mohorovičić discontinuity beneath the Antarctic ice sheet. The study of this problem may provide crucial evidence on whether or not this discontinuity is due to a phase change. If there is a change of material, a superimposed ice mass 3 km thick would only depress the discontinuity by around 1 km, which is not significant. On the other hand much larger changes may be possible if the discontinuity is a function of temperature and pressure as would be the case if the discontinuity is the product of a phase change. Both theoretical and experimental methods are needed for the solution of this problem.

Conclusion

In concluding this review, one must pay tribute to the vast number of scientists and technicians who have put up with the extreme discomforts and hazards of the polar regions to gather this vast collection of data which is advancing our knowledge of the polar regions at an unprecedented rate.

Scott Polar Research Institute
Cambridge.

References

Hamilton, R. A. & Others, 1956. "British North Greenland Expedition, 1952–4: Scientific Results", *Geogr. J.*, **112,** 203–240.

Hatherton, T., 1958. "Antarctic Research", *Nature* (*London*), **182,** 285–289.

Paterson W. S. B. & Slessor, C. G. M. 1956. "Trigonometrical Levelling across the Inland Ice in North Greenland", *Empire Survey Rev.*, **13,** 252–261.

Robin, G. de Q., 1955. "Ice Movement and Temperature Distribution in Glaciers and Ice Sheets", *J. Glac.*, **2,** 523–532.

Robin, G. de Q., 1958. Norwegian–British–Swedish Antarctic Expedition 1949–52, Scientific Results, **5,** Glaciology III, Seismic Shooting and Related Investigations. Norsk Polarinstitutt, Oslo.

Shoumsky, P. A., 1958. "Soviet Glaciological Exploration in the Antarctic Region", Paper presented to the 5th CSAGI Assembly, Moscow, August.

IGY Bulletins 1957–8 No. 1–14, U.S. Nat. Cttee for IGY. *Trans. Amer. Geophys. Un.*, **38, 39.**

IGY Glaciological Report Series No. 1, IGY W.D.C. "A". American Geographical Society, July 1958.

The 83rd Colloquium of the French National Centre of Scientific Research (Topography and Ecology of Oceanic Deeps) held at Nice, 1958 May 5-14

Representatives from Norway, Sweden, Denmark, Holland, U.S.A., Italy, Spain, North Africa and Great Britain attended this meeting, and a most useful exchange of ideas was possible, both between oceanographers from different countries and between specialists in subjects whose domains overlap. Not unnaturally, the Western Mediterranean basin was the subject of much discussion, and the combination of geological and geophysical work has produced some interesting ideas on the origin of the Mediterranean. It was an opportune moment for clarifying various viewpoints on Mediterranean structure, since not only is there considerable drilling activity in the area, but also the U.S. research ships *Vema* and *Atlantis* have been making a series of seismic measurements in the Mediterranean.

Full transcripts in French of all the papers have been made by the Colloques Internationaux du Centre National de la Recherche Scientifique (13, Quai Anatole-France, Paris 7e).

The colloquium at Nice will probably be remembered as marking the beginning of the bathyscaphe era in submarine geology. Slow development has been going on since the end of the war by the French Navy, the Belgians and the school led by Professor Picard. Funds for it have always been short, but successful dives have been made in the deep part of the Mediterranean and the difficulties and hazards of this type of work have been overcome. The U.S. Navy is now interested in bathyscaphes and is acquiring some for their own experimental work. There is little doubt that a rapid growth in bathyscaphe exploration of the sea-bed will soon follow.

The bathyscaphe enables oceanographers to have a direct look at what is beneath the sea surface and, in particular, what is on the sea bed. It should be possible to study deep-sea marine life with the help of the bathyscaphe. Knowledge of the animals that inhabit this domain is at present restricted to those bodies that can be brought to the surface in dredges and nets, and the habitat and behaviour of the animals is very much a matter of speculation in the dark. Photographs of the sea-bed have enabled marine geologists to formulate some ideas of the form of the deep-sea floor, and in some places ripple marks show the existence of currents in the water. However, a series of single photographic exposures, with a limited field of view, are not so useful as a continuous look from a vessel moving slowly at a short distance from the sea-bed. The shape of the sea-bed is known roughly from echo-sounders, but the detail is blurred because the echo-sounder is normally three miles above the sea-bed and records the depth to the nearest point, which may not necessarily be vertically beneath the instrument. It will be possible for the bathyscaphes to recognise whether topography that looks on the echo-sounder like hills and valleys is in fact similar to such features on land.

The bathyscaphe can obviously be of use in sample collecting. One is never sure that the corer goes into a typical part of the sea-floor, and much time and

effort could be saved by visual selection of the site. Current measurements could be made from the bathyscaphe at the sea-bed, and any movement of the sea-bed caused by storms on the sea-surface will be observed.

Professor L. Glangeaud described the Mediterranean as being neither an epicontinental sea like the Japan or China sea areas, nor an ocean like the Atlantic and Pacific with typical 6·7 km/s material close to the surface of the sea floor. From a geological study of the margins of the Mediterranean Professor Glangeaud has produced a mechanism of evolution for the Mediterranean which explains many of the geophysical and topographical data. The Mediterranean originally could have been a true deep ocean separating two continental sialic blocks—Europe and Africa. Normal denudation and sedimentation increased the size of these continents and, at the end of the Carboniferous period, the growth of the European and African Hercynian chains completely filled the gap separating Europe and Africa. Thus during the upper Permian and the lower Trias, an emerged continent stretched from England to the Sahara. There remained perhaps a few elements of the primary Paleotethys in the eastern Mediterranean, but there is no evidence to prove it. The sea reappeared from middle Triassic times and there is evidence which suggests that it did so because of a drifting apart of the European and African blocks. While such drifting is only postulated to meet the demands of surface geology, it is hoped that palaeomagnetic measurements may one day provide positive evidence. There is an increasing body of evidence that favours drifting of land masses; the mechanisms for such drift will no doubt be forthcoming when it has been demonstrated that they have, in fact, taken place. The latest evidence shows that rift valleys in the North East of Africa are formed by tearing apart the Earth's crust rather than by compressional forces and consequent pushing down of a block of material. If such drifting apart was a feature in Mediterranean evolution, it was followed by a phase in which the new sea again filled up and was raised in the Oligocene for a short period. From the time of the Miocene, sinking occurred and the sea covered the debris of the Alpine chain from the Carpathians in the north to the Saharian in the south —in much the same way as the Triassic sea had covered the debris of the Hercynian chain.

If this picture is substantially correct, the seismic measurements should show the Moho to be at a depth of ten miles or less below the sea-surface. The few refraction stations reported by Gaskell and Swallow in 1953 showed the presence of at least 2½ km of rock in which the compressional wave velocity was 4½ km/s. The energy propagation was bad and rough weather caused bad background noise during the observations and no 6·7 km/s refracting layer was detected. Unconfirmed reports from the U.S. Mediterranean expedition of 1958 suggest that the same bad propagation was experienced and that the structure of the deep Mediterranean basins is still undetermined. No doubt there will be some depression of the original ocean floor, due to the abnormal amount of material deposited since the Mediterranean was a true ocean. In fact, although Professor Glangeaud asserts the contrary is true, it is possible that the Mediterranean is similar to the Japan sea region, where several kilometres of rock in which the compressional wave velocity is about 5·8 km/s are found below the sea-bed instead of the usual 6·7 km/s found in other oceans.

Professor Kuenen, on the other hand, was of the opinion that the Mediterranean is an example of turning continental into oceanic type by some form of melting or dissolving of the granitic layer, together with the dropping of a whole block.

There certainly needs to have been a large mass of material to provide the sediments of the Alps and the Sahara.

The topography of the deep oceans was discussed by *Dr Menard* of the Scripps Institution of Oceanography. *Menard* has calculated that there are about 5–10 000 atolls, volcanos, guyots and sea-mounts in the Pacific. This figure is estimated from the value of 800 already discovered and the fact that only 10 per cent of the Pacific has been explored; from the length of track of ships with echo-sounders and the value for number of features per mile of track; and thirdly by taking a well-explored area and extrapolating. This large number of sea-bed features means that the Pacific consists of a series of small hills protruding from a flat base. Around the larger features are smooth areas that *Menard* has called archipelagic aprons—these are large compared to their parent volcanos and therefore are probably formed by erupted volcanic material rather than by sediment derived from the erosion of the volcanos. On this picture, the area of sea bed smoothed by volcanic outpourings is as great as the flat areas produced by submergence of sea-bed features by sediments moved by turbidity currents. The same topographical features probably occur in other oceans, but so far only a small line of flat topped sea-mounts has been found in the Atlantic. The deep-ocean seismic results summarized by *Gaskell* suggest that there is a difference between the Atlantic and the Pacific. The Atlantic—at least over the greater part of its area—can support volcanic features that grow from the sea-bed and it is possible that this is due to a hardening of the rock that comprises the sea-bed. It is significant that the places where hardening of the rock is needed to explain the non-sinking of volcanic islands are just those where continental drift has been postulated. It could be that movement of continental areas leaves an altered 6·7 km/s layer (or sima layer) which is more rigid than the original ocean floor. On this hypothesis, of course, the continental drift is irreversible because it can only take place into the slightly plastic primaeval ocean floors.

Dr Heezen of Woods' Hole showed his new charts of the underwater topography of the Atlantic Ocean. These charts are made so that the different sea-bed topographical features—mountain ranges, isolated volcanos, flat abyssal plains, etc.—stand out clearly. They may be obtained from The Geological Society of America, 419 West 117 Street, New York 27, N.Y. Part I of Special Paper 65, *Physiographic Diagram of the North Atlantic, Sheet* 1, by Bruce C. Heezen and Marie Tharp is issued, price $1.50 per copy. Part 2, the text, by Heezen, Tharp and Ewing, consists of 150 manuscript pages, 49 figures and 30 plates, and is in press. *Dr Heezen* suggested that the evidence of such features as the rift in the Mid-Atlantic Ridge, and the recent evidence that the African rift valleys are due to tension rather than to compression, indicate that the Earth is expanding, and therefore a warming-up, not a cooling-down, is taking place. Warming-up is postulated by those who would build the Earth by collection of material from outside the Earth. A recent paper in the *Geophysical Journal* by Dr Lubimova (1958) maintains that the combination of radioactivity and poor conductivity of the rocks that constitute the Earth must mean that the inside is getting hotter—although the outside crust could have cooled in the past. This could well explain Heezen's rift zones.

Sediments in the deep sea were the subject of *Dr Wiseman's* paper. *Dr Wiseman* stressed the need for great care in taking of deep sea cores. Apart from the technical point of disturbing the layering of the core by unsuitable design of coring device, the actual location of the core is of paramount importance. For example, cores from abyssal plains and from continental rises are unsuitable for studying past

temperature changes in the sea because the sediments will have been subjected to slumping and to erosion. Movement of sediment by such burrowing animals as holothurians or by 'sand volcanos' must also be avoided. *Dr Wiseman* suggests therefore that cores should be taken from the top of an isolated knoll.

Professor K. O. Emery of the University of Southern California described his work on the sediments of the continental borderland of S. California. The rate of sedimentation is measured by making ^{14}C analyses on core-samples and ranges from 20 mg/cm^{2}yr at the bottom of the basin to 60 mg/cm^{2}yr nearer land. A rate of 50 mg/cm^{2}yr corresponds to about 1 mm thickness of deposit per year at the sea-bed, so that these figures are about ten times the values found in the deep oceans. Some care must be taken in the carbon age determination because the age at the top of the core is found to be 2 000 years, and this value must be subtracted from the age of sections of the core lower down in order to obtain the correct deposition rate.

Dr Landergren proposed the use of the measurement of the boron content of sediments in order to determine salinity conditions when sediments were deposited.

A visit was paid to the National Museum of Oceanography at Monaco. This museum has an aquarium and a fine collection of old oceanographic devices. In addition to modernizing the lay-out of the exhibition, the Director, *Commandant Cousteau*, proposes to follow the wishes of Prince Albert of Monaco, the founder of the museum, by doing as much deep-sea oceanography as possible.

The museum hopes to develop techniques which will enable difficult experiments to be carried out at sea. The underwater diving with the aqualung has proved of great value in studying underwater geology, and *Commandant Cousteau* described the work he is now doing on the use of nylon cables for dragging dredges and for anchoring ships in deep water.

Two of the three directors of the International Hydrographic Bureau presented papers during an afternoon visit. *Director Viglieri* described the progress of the latest revision of the Monaco Hydrographic maps and spoke of the co-operation that has been arranged with the various national hydrographic services. *Director Damiani* discussed the present state of agreement and disagreement on the subject of nomenclature of ocean bottom features.

The Colloquium closed with the official inauguration of the Oceanographic Station at Villefranche-sur-Mer (Director: Professor J. Bourcart).

References

Gaskell, T. F. & Swallow, J. C., 1953. *Nature* (*Lond.*), **172**, 535.
Lubimova, H. A., 1958. *Geophys. J.*, **1**, 115.

Book Reviews

Principles of Geodynamics

Adrian E. Scheidegger

xi + 280 pp. (Springer–Verlag)

Dr Scheidegger remarks in his preface "It seems, therefore, that the time is ripe for an evaluation of existing ideas (on geodynamics) in the light of presently available facts". This is undoubtedly so, and it is time for a critical review of facts and theories about such topics as the origin of continents and oceans, the formation of geosynclines and mountains, and earthquake and volcanic activity. Unfortunately this book just misses being the review that is needed. The title itself is rather misleading. The successive chapters are summaries of physiographical, geological and geophysical facts concerning the Earth; of the mechanics of deformation and theories concerning the effects of the rotation of the Earth and of ideas that have been put forward about the formation and growth of continents and oceans, orogenesis, faulting and folding and miscellaneous minor features. It is, however, disappointing that there is little discussion of principles, in the sense of conditions to which all theories should conform—a sort of geophysical "fence" to bound future arguments. It might be thought that these conditions are obvious, but in view of the evident difficulties of the subject, stemming from the fact that we can observe only the state of the surface of the Earth at the present moment of time, it is surely worthwhile to attempt to make these principles explicit. Almost everyone, for instance, tacitly assumes that the behaviour of the Earth is governed by the laws of classical physics, although Egyed has argued that some phenomena are the consequence of changes in the "constants" of physics that, it has been suggested, are entailed by general relativity. (Professor Wilkinson has adduced evidence from pleochroic haloes to argue that changes in fundamental atomic constants are extremely small (Wilkinson 1958).)

Another principle to which most theories seem to conform is that the state of the Earth in the past should be assumed to be much as it is today. Geologists especially have been very successful in interpreting their data on this basis, a success which may have obscured the fact that classical geology has dealt only with the last third or quarter of the Earth's history and that the origin of the continents, for instance, seems to be early in the Earth's history. In one respect at least it is untrue that the present state is representative of the past, for if the usual laws of physics are supposed to apply, then the present stock of radioactive matter is less than the original. Estimates of the importance of this factor depend on the assumed initial temperature distribution in the Earth, since this determines the proportion of the present efflux of heat that is due to radioactivity. Our views on the heat energy available for geodynamic processes at any time in the Earth's history must therefore depend on our views about the origin of the Earth. In this connection, one would welcome a discussion of the sources of available energy. It usually seems to be assumed that these are either stored heat from the Earth's

initial state or energy stored in radioactive nuclides. There is also the kinetic energy of the Earth–Moon system and, if there are phase changes within the Earth, energy would have been released from low-pressure forms of minerals as the Earth condensed (whether from gas or from solid particles). It would, incidentally, be useful to know the time constant for such phase changes.

The only section of the book in which principles in this sense are discussed is the chapter on the mechanics of deformation. The importance of a very careful study of this subject cannot be overemphasized, and sophisticated summaries are given of the theories of finite strain, of infinitesimal elastic deformation and of some ideas of plasticity and hydrodynamics. Unfortunately the parts of the subject with the most sophisticated development are those that are of least use in geodynamics and the balance of this chapter, although it reflects the present state of knowledge of the deformation of solids, does not reflect the relative importance of the parts of that subject to geodynamics. The primary difficulty here, as in most aspects of geodynamics, is the gross discrepancy between the time scale of natural events and that of anything we can observe. Accordingly, although various effects may be identified as resulting from certain types of rheological behaviour, an enormous extrapolation is involved and it is arguable that it may in future be possible to establish the rheological behaviour theoretically from the theory of solids with more certainty than it can be inferred from experimental observations—this may even now be the case in the analogous problem of estimating the equation of state of matter in the core of the Earth. Dr Scheidegger gives us a useful summary of the evidence for the types of rheological behaviour in the Earth's crust for different time scales but part of this is now superseded since Sir Harold Jeffreys has shown that the law propounded by Lomnitz fits various observations rather well. But not only is the physical behaviour of matter over long intervals very poorly known; in addition the mathematical theory of the motion of bodies following rheological laws that may hold for the Earth has important gaps. Dr Scheidegger mentions the most serious of these gaps—the study of rheological instability—and remarks that mountain ranges are probably the manifestations of lines of instability. Bijlaard has considered instability of a plastic material in tension but this is clearly irrelevant to the problem of orogenesis, where it seems that instability in compression occurs. It is likely that allowance must be made for the weakening of the crust due to heating by the blanketing of sediments once a geosyncline has started to form. Another example of instability is probably the flow of rocks producing the folds characteristic of mountains. The patterns of these folds are very reminiscent of instability in hydrodynamic flow or magneto-hydrodynamic phenomena where a displacement gives rise to forces tending to increase the curvature of the flow line or line of force.

In view of Dr Scheidegger's aim of confronting the various theories of geodynamical problems with the available facts, one would have wished for a more extended critical discussion of these facts instead of the rather condensed summary that is given. This, to my mind, is the main weakness of the book. It is very useful to have the theories most competently summarized, but one feels that with a fuller discussion of the facts and their significance this book would have begun a new advance in these studies.

One point that might have been discussed in more detail with quantitative data is the significance of isostatic balance and the departures from it, particularly so far as inferences can be drawn about the strength at different levels in the Earth. The very similar rates of flow of heat from continents and oceans is another

important fact, while the different depths of the Mohorovičić discontinuity below continents and oceans and the different chemical constitutions of the crust deserve more than mere statement. But attention should also be called to the differences between one ocean and another, such as the clear distinction between the topography of the floor of the Atlantic and Pacific oceans. The mass of detail we have about the continents may obscure equally great distinctions between continents, a striking instance being the great mountainous areas of Central Asia which have no parallel elsewhere and which find no explanation in any of the usual theories of mountain building. It is not Dr Scheidegger's fault that his section on palaeomagnetic data will certainly soon be out of date, for this is a rapidly developing subject; the data so far come entirely from the continents but in view of the inference of continental movement that has apparently to be drawn it would be worth considerable effort to attempt to obtain similar data from oceanic regions.

In considering the origin of mountains, Dr Scheidegger introduces a relation between the cross-sectional area of a mountain range and the apparent shortening suffered by the rocks. The relevance of this apparent shortening, inferred from the folding of the visible rocks, requires more critical discussion. One may certainly distinguish between the deformation of the crust and that of the much weaker geosynclinal deposits above it and it has already been suggested that the pattern of the latter is comparable with patterns of unstable flow. Geologists have, in fact, sometimes suggested that nappes result from the sediments sliding down the slopes of a rising crust. If these ideas have substance, then the apparent shortening is irrelevant to the main problem, that of the deformation of the crust. This might profitably be considered in terms of energy balance. The excess potential energy of a mountain may be estimated from its topography and gravity anomalies and the shortening may be estimated from the supposition that the cross-sectional area is unchanged in the deformation. Then the maximum work done is the product of the shortening by the strength of the undeformed crust and this must equal the potential energy of the mountain range plus any dissipation in plastic deformation. The latter is the most difficult to estimate and more theoretical work on losses in plastic deformation would be required; this, by the way, might be a more profitable field for model studies than investigation of the geometry of deformation. It can however be estimated that the latent heat of a large batholith is only a small fraction of the potential energy of a typical mountain range so that the formation of batholiths may, so far as energy considerations go, be regarded as incidental to the formation of a mountain. This is a very simple-minded study proposal and a considerable difficulty in putting it into effect would be deciding to what depth the deformation can be considered to extend.

One may think of the crustal boundary as a chemical or phase boundary, a density boundary or seismic boundary, a stress boundary or a strain boundary. The seismic boundary is the only one that is well established and it is more than a little naïve to suppose that all the others coincide with it and form a well-greased surface over which the crust may slide. The association of deep focus earthquakes with geosynclines shows that there is no firm stress or strain boundary at the Mohorovičić discontinuity and a deep seismic boundary is not always found where indicated by gravity anomalies.

Of the many concepts of orogenesis, that of the "tectogene" as a buckled region in the crust should certainly be forgotten. It should never have been given currency as the idea of a region in which the inclination of the crust was so great that the engineering theory of elastic buckling applied. This probably arose from

misleading diagrams with exaggerated vertical scales, but in fact there is no evidence that the crust deforms in this way and Dr Worzel has now shown that gravity anomalies over island arcs indicate a thinning rather than a thickening of the crust. In considering the development of a geosyncline, it is probably wrong to think of sediments accumulating uniformly along the length of the geosyncline. No other geosyncline has been studied in such detail as the Welsh geosyncline and there Jones's (1956) results show how at one period the sediments accumulated with their greatest thickness first in one part, then in another of the geosyncline, until the whole geosyncline was filled up. The thick sediments were almost entirely deposited in shallow water so that one has to think of the major depression of the crust occurring in different places at different times, with strong indications that the local rate of change of depression is too great to be accounted for by elastic flexure of the crust.

Dr Scheidegger makes one point in his discussion of theories of orogenesis that is questionable. He says (p. 161) that metamorphism is associated with increase of density. If, however, the formation of granite is regarded as the final stage of metamorphism, as Dr Scheidegger seems to accept, then this is not true, for it is well known that granites are almost always less dense than the country rocks, even where the latter are scarcely more than highly compact sediments.

Another question to which more attention might be given is classification of the types of deformation that are found. Mountains are fairly obviously the result of compression while it seems very likely that rift valleys are due to extension, and now current work on earthquakes round the Pacific suggests that the predominant motion is a rotation of the Pacific relative to the surrounding land.

This is certainly a useful book bringing together all the current and past theories and confronting them with observation at a time when new discoveries, such as those that may be made when a borehole passes through the Mohorovičić discontinuity, may turn the subject upside down. A very valuable feature is the extensive reference to recent Canadian and Russian work and the book owes much to the author's association with Toronto and Ottawa. While it is remarkably up-to-date, containing for example a number of references to papers read at the I.U.G.G. meetings at Toronto in September, 1957, the book also shows some surprising omissions from the literature, for instance the work of Jeffreys and Bland (1957) on convection in the mantle of the Earth. There are also indications that the author was not clear for whom he was writing, for some things, such as the principles and methods of seismology, are explained in a very elementary way while others, like the theory of finite deformation, receive an advanced treatment.

The printing and diagrams are excellent and there are full author and subject indices, but the English reader may often be brought up sharply by the use of "lap" meaning "laplacian", while there are several annoying minor misprints.

There is no doubt that this book deserves careful study by everyone with a serious interest in its subject.

A. H. Cook.

References

Wilkinson, D. H., 1958. *Phil. Mag.* (8) **3**, 581.

Jones, O. T., 1956. *Quart. J. Geol. Soc. London*, **111** (for 1955) 323.

Jeffreys, H. & Bland, M. E. M., 1951. *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, **6**, 148.

Geophysics Series of the Bulletin of the Academy of Sciences of the U.S.S.R., No. 1.

Pergamon Institute (£9. 10. 0. per year, monthly)

This is a well-produced translation of what is presumably the Russian equivalent of the *Geophysical Journal*. Since geophysics is becoming more international in flavour and since many opportunities now occur for English-speaking and Russian geophysicists to meet, it is desirable that each should be able to read what progress the other is making. The Royal Astronomical Society has made a notable advance in one direction by providing summaries in Russian of all its published papers, and it is pleasing to see that the Pergamon Institute are now providing the full text of the Russian geophysical papers.

The Russian journal makes a distinction between Terrestrial Physics and Atmospheric Physics. In the present number there are eight papers in the first group and three in the second. In this country the papers in the Atmospheric Physics group, which are about waterspouts, clouds and raindrops, would probably have been in journals other than the *Geophysical Journal*, but all the papers on Terrestrial Physics are of the type that might be published in the *Geophysical Journal*.

The first paper is a review article which describes the present position of seismology in the Chinese Peoples Republic and ends with a short fanfare praising the work of the Communist party.

There are two seismological papers which relate observations to crustal structure and a gravity paper giving a new method for reduction of results and correcting for topographical features. This last paper would really be more suitable for a publication dealing particularly with exploration geophysics, as would that on "Frequency Investigations in Detailed Electrical Prospecting".

The wide variety of subjects that are covered includes magnetism, and results are given ot experimental studies of the stability of the magnetic fields of rocks. Another paper describes the equipment used to measure the natural electromagnetic field of the Earth in the frequency range 2–300 c/s. This work has been done in order to develop a survey method.

The last paper described the effect of turbulence on the formation of riverbeds. It is concluded that the water currents of the Earth spend their energy largely in overcoming hydraulic resistance, and only to a few per cent on processes of erosion.

There is a section of the journal which includes Reports and Notes on such practical subjects as gamma-ray well-logging and new seismograph design. Two of the Notes describe astronomical work (velocity of corpuscles projected from the Sun and the effect of meteoric streams on the electric field of the Earth's atmosphere) which would be placed by the R.A.S. in its *Monthly Notices*.

The U.S.S.R. Geophysics Series No. 1 indicates that Russian thought is along the same lines as in this country. There is nothing particularly new in any of the papers in this first translation, and in some ways the journal is more suited to the

practical oil or mineral prospector than to the seeker after fundamental principles of the construction of the earth.

Some of the translation is a bit heavy; "expeditionary investigations" on p. 9 and "cavernometry" on p. 130 sound a little odd.

The price of the journal is really out of reach of the already overburdened individual geophysicist; he will be better served by buying the individual papers of interest to him from one of the several organizations that now provide a Russian translating service. The subjects covered are too diverse for any one research person but the journal might be useful to have in a reference library.

T.F.G.

РЕЗЮМЕДОКЛАДОВ, В ПЕРЕВОДЕ НА РУССКИЙ ЯЗЫК

СМЕШИВАНИЕ ПРИЛИВОВ И ОТЛИВОВ В УЗКИХ МЕСТАХ УСТЬЯ РЕКИ МЕРСЕЙ

П. Юз

Измерения солёности в узких местах реки Мерсей указывают на то, что вертикальное смешивание из-за турбулентности вызванной приливом, может окончиться до середины прилива. При затухании приливных течений возникают горизонтальные дифференциальные скорости, направленные в море в верхнем слое и вверх по течению реки у ее дна, приводящие к вертикальным градиентам солёности. Другая серия наблюдений указывает, что если течение реки сильно, то однородность по вертикале может вообще не быть достигнутой. Применяя эту теорию к устью, в котором происходит вертикальное смешение, вычислены коэффициенты продольной вихревой диффузии для слабого течения реки (26 м³/сек.), дающие среднюю величину в 160 м²/сек. Во время более сильного прилива пресной воды (103 м³/сек), когда условия бывают менее определённы, средний коэффициент становится значительно больше—360 м²/сек.

О ХИМИЧЕСКОМ СОСТАВЕ НАРУЖНОГО ЯДРА ЗЕМЛИ

Гордон Дж. Ф. МакДональд и Леонид Кнопов

Считается, что средняя структура Земли совпадает со структурой хондритных метеоритов. Это предположение совместимо с настоящей скоростью выделения тепла в Земле. Ядро, состоящее только из железа и никеля, невозможно согласовать с хондритной моделью, кроме того случая, когда отношение (Fe+Mg)/Si в оболочке Земли равняется единице. Для того, чтобы (Fe+Mg)/Si=1, надо, чтобы большая часть оболочки Земли состояла из материала, подобного по структуре пироксену или пироксену и гранату (эклогиту). Если считать, что оболочка Земли состоит из слоя толщиной в 400 км, имеющего структуру эклогита, под которым находится материал структуры дунита, то по хондритной модели ядро должно состоять из вещества $(Fe, Ni)_{1,6}Si$.

Введен средний атомный номер ($\bar{Z}$) для характеристики соединений при умеренно высоких давлениях. Вычисление $\bar{Z}$ выполняется на основе асимптотических отношений модели Томас-Ферми-Дирак'а. Из распределения плотности по Буллену, для наружного ядра $\bar{Z}$ получается приблизительно 22. Средний атомный номер для $Fe_{1,6}Si$=22,8. Таким образом, вещество ядра, выведенное из уравнения состояния, совместимо с хондритной моделью Земли.

При полученной структуре ядра, электрическая проводимость $(Fe, Ni)_{1,6}Si$ должна быть между третью и одной десятой проводимости железа. Такая проводимость совместима с требованиями теории магнитного поля Земли.

НОВОЕ ОПРЕДЕЛЕНИЕ РАЗНОСТИ СИЛЫ ТЯГОТЕНИЯ МЕЖДУ ИЗМЕРЕНИЯМИ В НАЦИОНАЛЬНОЙ ФИЗИЧЕСКОЙ ЛАБОРАТОРИИ В ТЭДДИНГТОНЕ И В ОСНОВНОЙ, А ТАКЖЕ ВО ВТОРИЧНЫХ СТАНЦИЯХ В ЮЖНОЙ АФРИКЕ

Д. И. Гоф

Наблюдения производились при помощи маятникового прибора Кэмбриджского типа на основной британской станции по измерению тяготения при национальной физической лаборатории в Тэддингтоне, на основной южно-африканской станции по

измерению тяготения в Иоханнесбурге* и на южно-африканских вторичных базовых станциях в Претории и в Моубрэй. Во время испытаний два маятника нечаянно подверглись действию ртути. Остальные четыре, а именно IA, IB, IC и VIA, определяют средние разности силы тяготения

Тэддингтон-Моубрэй $=1{,}5495 \pm 0{,}0001$ см/сек^2
Тэддингтон-Иоханнесбург $=2{,}6472 \pm 0{,}0003$ см/сек^2
Тэддингтон-Претория $=2{,}5672 \pm 0{,}0003$ см/сек^2

отсюда, принимая в Тэддингтоне $g=981{,}1963$ см/сек^2
в Моубрэй $g=979{,}6468$ см/сек^2
в Иоханнесбурге $g=978{,}5491$ см/сек^2
в Претории $g=978{,}6291$ см/сек^2

Эти величины хорошо совпадают с определениями в 1948–9 гг. Хейлса и Гофа.

*Пока не решено формально будет ли станция в Иоханнесбурге основной станцией в Южной Африке, но она уже является первоклассной южно-африканской станцией в международной сети.

МАГНИТНАЯ ОЧИСТКА ГОРНЫХ ПОРОД ПРИ ПАЛЕОМАГНИТНЫХ ИССЛЕДОВАНИЯХ

Дж. А. Ас и Дж. Д. А. Зейдервельд

Известно, что остаточный магнетизм горных пород часто является равнодействующим двух намагничиваний: во-первых, намагничивания со слабой коэрцитивной силой, направление которого обычно определяется местным полем Земли в настоящее время во-вторых, намагничивания с сильной коэрцитивной силой, направление которого определено полем во время образования породы.

Определено, что можно устранить возмущающее намагничивание слабой коэрцитивной силы, сохранив при этом большее количество намагничивания ископаемого, при помощи частичного размагничивания. Это достигается сочетанием переменного возбуждения и нагревания.

Обыкновенно, размагничивание с переменными полюсами возбуждения до 300 эрстед (эффективных) при температуре в 150°Ц. являлось достаточным для очистки горных пород.

МАГНИТОРАЗВЕДКА У ЗАПАДНОГО БЕРЕГА С.Ш.А. МЕЖДУ 32° И 36° С.Ш. И МЕЖДУ 121° И 128° З.Д.

Р. Г. Мейсон

Приведена карта общей магнитной интенсивности для обдасти между 32° и 36° с.ш. и между 121° и 128° з.д. На ней обозначается ряд узких аномалий, амплитудой приблизительно в 400γ, протянувшихся с севера на юг на 500 км среди существенно ровной абиссальной плоскости. Обсуждаются некоторые возможные интерпретации. Аномалии залегают на небольших глубинах под ложем океана и совместимы с наличием относительно тонких слоев намагниченного вещества, расположенного поверх менее намагниченной коры. Они могли бы также возникнуть из-за топографического рельефа верхней поверхности непрерывного магнитного поля, прикрытого в большей части слоем осадков.

Аномалии пересекаются зоной изломов Муррэя, прерывающей их очертания таким образом, что можно предположить боковое смещение вправо на приблизительно 155 км.

ИССЛЕДОВАНИЕ КАЛИБРИРОВАНИЯ ПРИБОРОВ ДЛЯ ИЗМЕРЕНИЯ СИЛЫ ТЯЖЕСТИ

Р. Л. Г. Гильберт

При измерениях силы тяжести, распространяющихся на зону большого изменения ее, выяснилось, что приборы менее надежны чем предполагалось. Приведены цифры ошибок, найденных при пользовании тремя приборами измерения силы тяжести, при-

меняя различные методы исследования, а также разбираются некоторые возможные причины ошибок. Доказывается, что постоянныя шкал приборов со временем существенно изменяются и описывается система проверки этой постоянной, включенная в один из приборов для контроля постоянной в любое время. Данные, полученные при помощи этого приспособления, приведены в таблице и обсуждаются; небыло найдено удовлетворительного способа, объясняющего изменение постоянной шкалы, а прибор калибрирования оказался полезным в некоторых случаях, но не настолько, насколько предполагалось.

В заключение выводится, что для точного измерения больших разностей силы тяжести, необходимо осторожно пользоваться приборами, регулярно проверяя калибрацию прибора и что следует предпочесть измерения при помощи маятников в случаях измерений очень больших разностей тяготения.

ОПРЕДЕЛЕНИЕ ГРАВИТАЦИОННОГО ПОТЕНЦИАЛА ЗЕМЛИ ПО НАБЛЮДЕНИЯМ НАД ВТОРЫМ СПУТНИКОМ ЗЕМЛИ (1957β).

А. Х. Кук.

Наблюдения королевского авиационного общества над скоростью вращения орбитальной плоскости второго Спутника сочетаются с уравнениями Джеффриса (1943 1952) для коэффициентов **J** и **D**, входящих в разложение гравитационного поля Земли по сферическим функциям, с целью переоценки величин **J** и **D**. Относительная неопределенность результатов указывает на ценность наблюдений над спутниками Земли и на необходимость переоценки анализа по сферическим функциям силы тяжести на поверхности Земли.

Geophysical Journal

RECOMMENDATIONS TO AUTHORS

1. Authors are advised to follow the general suggestions for the preparation of scientific papers given in *Notes on the preparation of papers to be communicated to the Royal Society* and in *The printing of mathematics* by T. W. Chaundy, P. R. Barrett and C. Batey (Oxford University Press, 1954). In particular the abbreviations for the names of periodicals used in the *Geophysical Journal* are those given in *Notes on the preparation of papers* . . . and the symbols, signs and abbreviations are those recommended for British scientific publications by the Symbols Committee of the Royal Society.

2. Papers should be typewritten with double spacing and on one side of the paper only. Two copies, one of them the top copy, should be submitted. All papers must be accompanied by a summary; summaries are not required for *Letters to the Editors*.

3. Tables are printed without rules. They should be numbered serially with Arabic numerals. Table headings should be brief. Units should be placed at the head of the column. Tables should be typed on separate sheets and their positions in the text indicated on the copy.

4. Illustrations, especially photographs, should be kept to a minimum, and the same information should not in general be given in both tables and illustrations. Line drawings should be in dense black ink on smooth white board or transparent tracing film. Original drawings must not be lettered; lettering should be indicated on copies or photoprints which must be supplied in addition to the originals. Wherever possible, lettering should be kept outside the diagram so that it may be set in type. Diagrams should be drawn at twice to three times the size at which they will be printed. The maximum dimensions for diagrams, when reduced and with their lettering and captions, are 8 in by 5 in. A wide variety of flat tints of dots, lines and shadings can be applied to line drawings by the blockmaker. Photographs for reproduction should be unmounted glossy prints and should be accompanied by lettered prints.

5. References should be quoted in the form recommended by the Royal Society but authors may also quote titles of papers if they wish. References in the text are made in the form (Smith 1940).

6. Authors whose work involves much mathematics should follow carefully the recommendations in *The Printing of Mathematics*.

7. The Editors will be glad to advise authors on any special points of difficulty arising in the preparation of papers for the *Journal*.

Contents

PAGE

P. HUGHES, Tidal mixing in the narrows of the Mersey estuary 271

G. J. F. MACDONALD and LEON KNOPOFF, The chemical composition of the outer core 284

D. I. GOUGH, A new determination of the differences in gravity between the N.P.L. Teddington and the South African fundamental and secondary stations 298

J. A. AS and J. D. A. ZIJDERVELD, Magnetic cleaning of rocks in palaeomagnetic research 308

R. G. MASON, A magnetic survey off the west coast of the United States between latitudes 32° and 36° N and longitudes 121° and 128° W 320

R. L. G. GILBERT, An investigation into the calibration of gravity meters 330

Research Note

A. H. COOK, Determination of the Earth's gravitational potential from observations of Sputnik 2 (1957β) 341

Letter to the Editors

W. D. PARKINSON and J. CLEARY, The eccentric geomagnetic dipole 346

Note on progress in Geophysics

G. DE Q. ROBIN, Geophysical studies in polar regions: the Antarctic ice sheet 347

Report on the 83rd Colloquium of the French National Centre of Scientific Research (Topography and Ecology of Oceanic Deeps) held at Nice, 1958 May 5–14. 352

Book Reviews 356

РЕЗЮМЕ ДОКЛАДОВ, В ПЕРЕВОДЕ НА РУССКИЙ ЯЗЫК 362

Printed in Great Britain by J. W. Arrowsmith Ltd., Bristol